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Padova, 16-18 September 2025

ABSTRACT BOOK

a cura della Società Geologica Italiana

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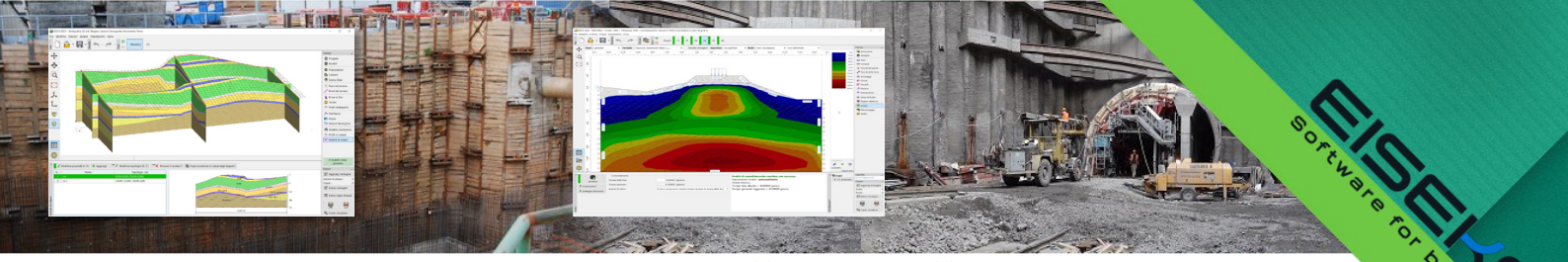
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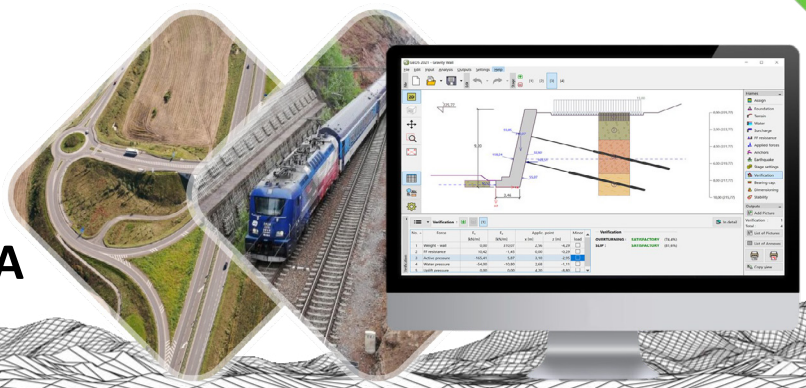
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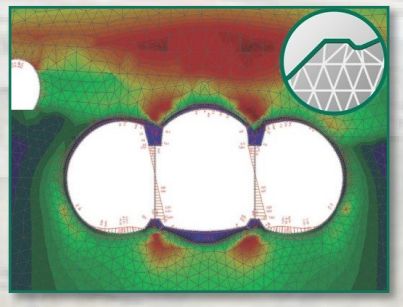
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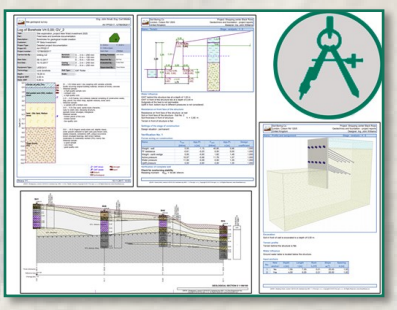
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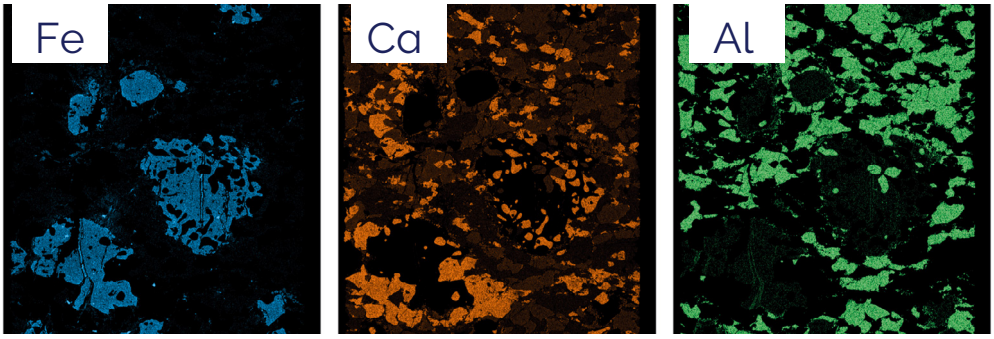
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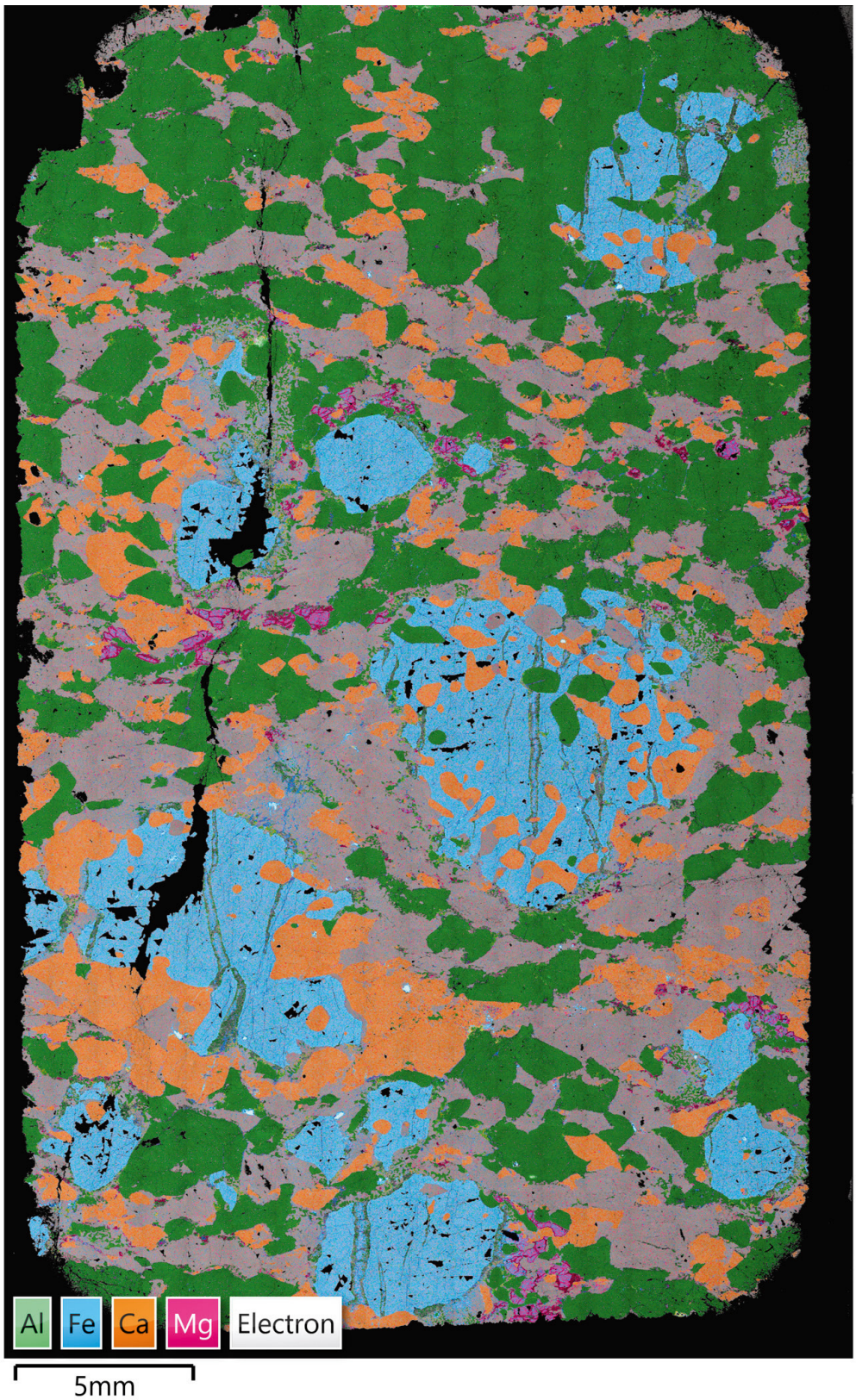
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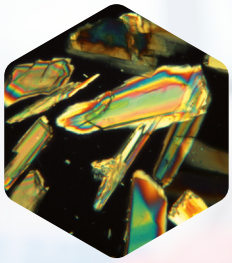
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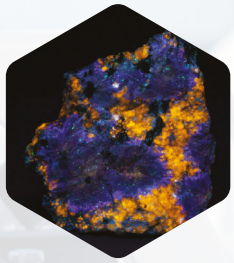
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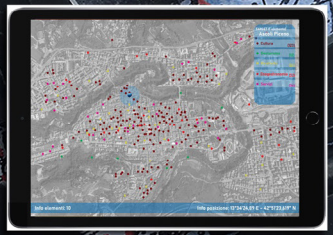
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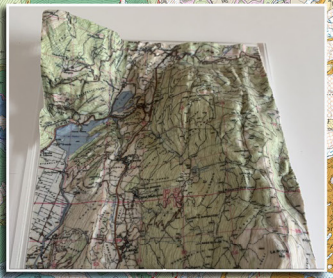


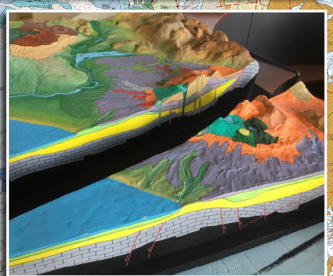




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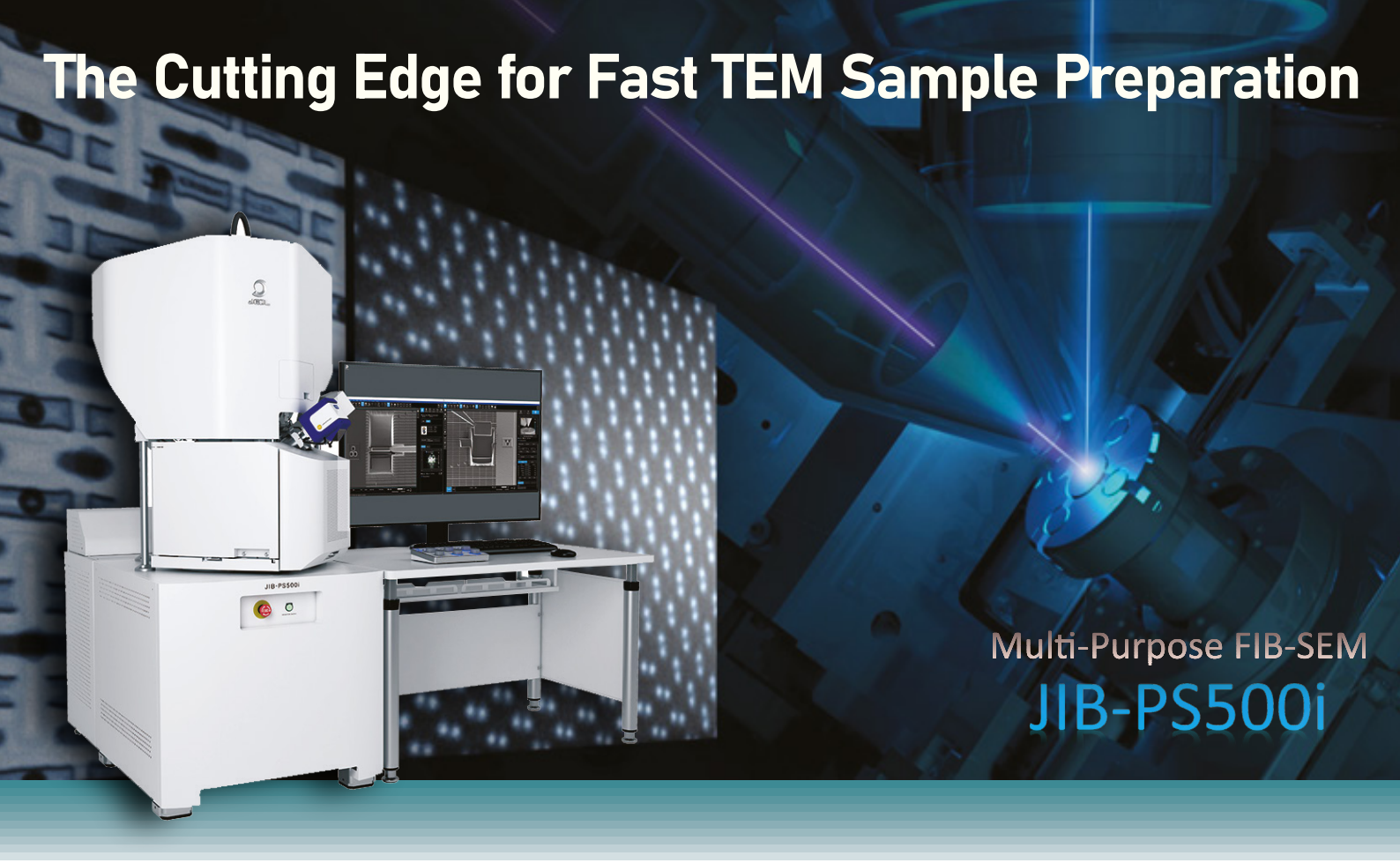
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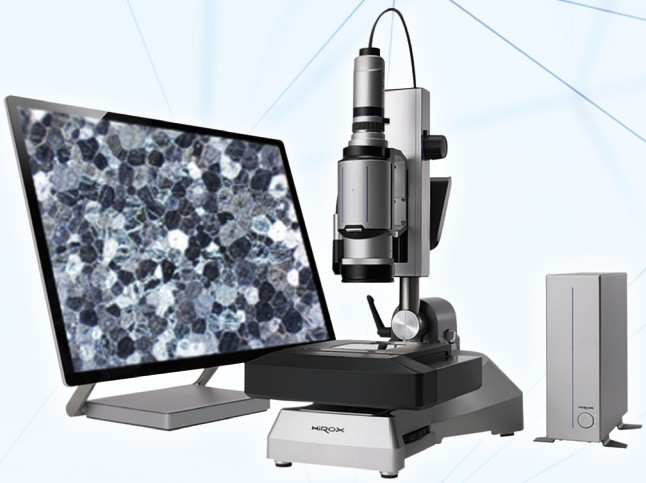
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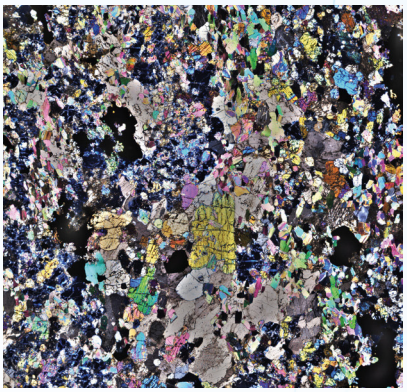
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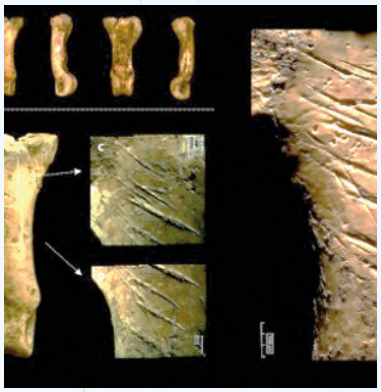
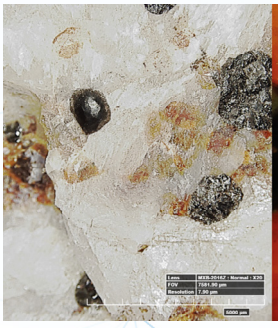
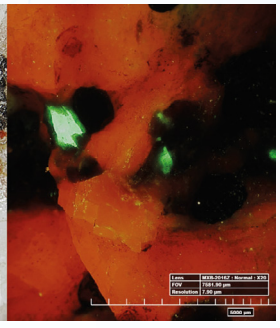
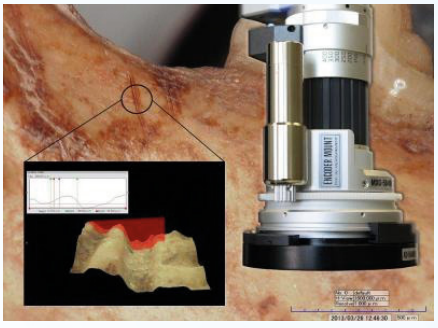
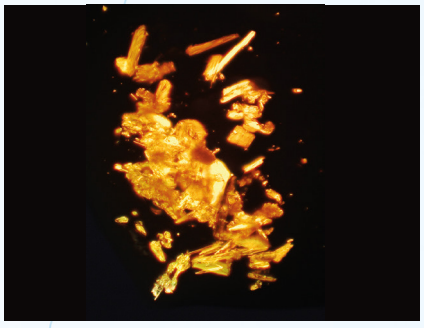
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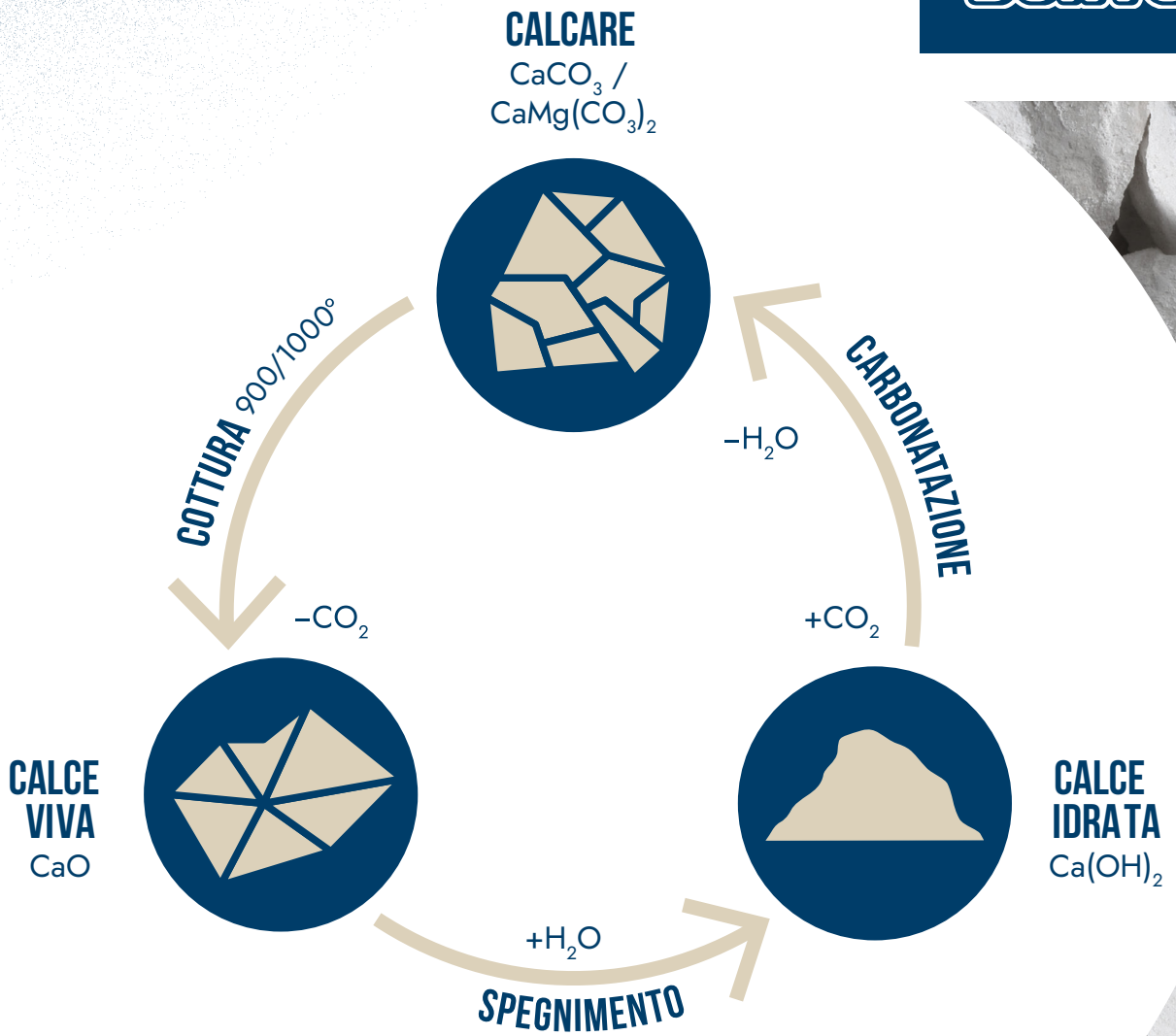
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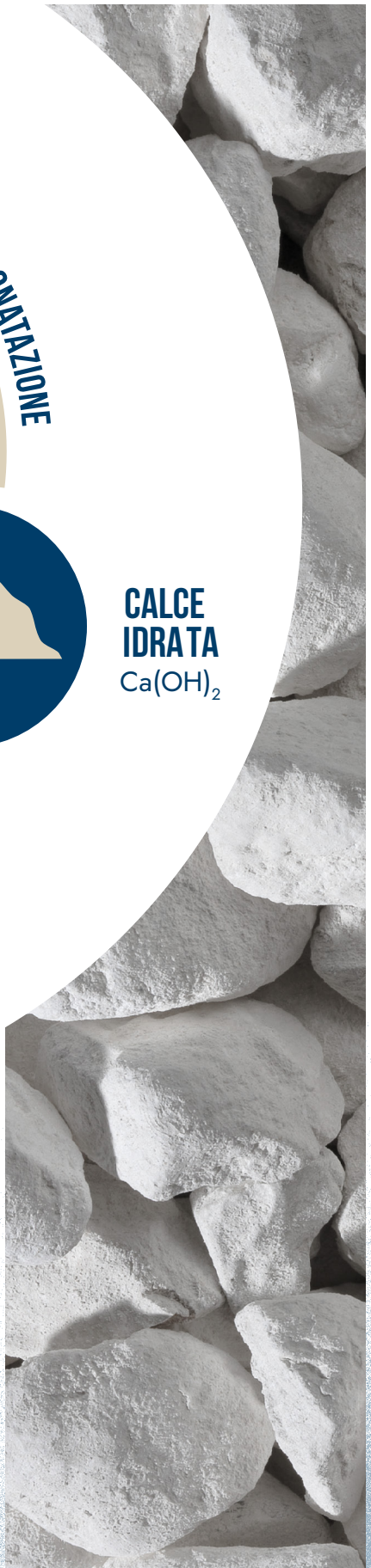
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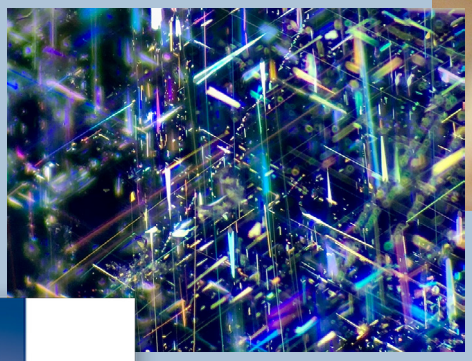
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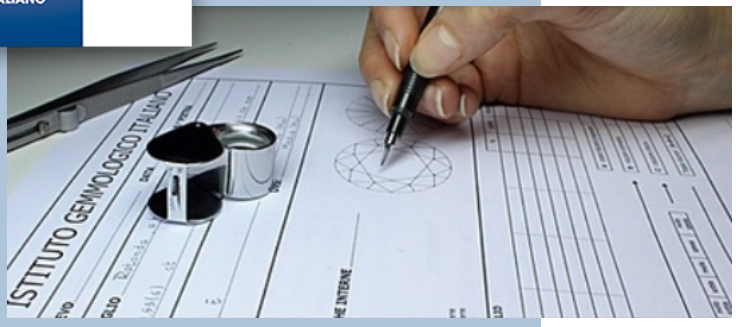


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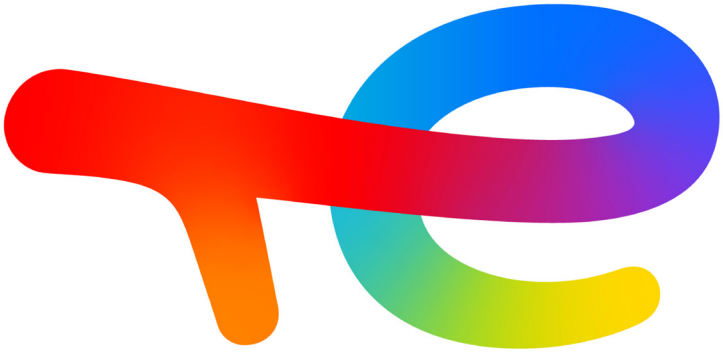








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PLENARY SESSIONS

Multimodal and multiscale microscopy for advanced characterization in geosciences

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Keywords: multimodal microscopy, geosciences, elemental mapping.

Multimodal microscopy offers a powerful, integrated approach for morphological, structural, and chemical characterization across multiple scales. By combining light microscopy (LM), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray microscopy (XRM), researchers can achieve synergistic 3D reconstructions, elemental mapping, and phase identification. This approach has broad applications in many fields, such as geology, cultural heritage, environmental, and materials sciences. A notable example in the geosciences is the work by Giuntoli et al. [1], where a correlated microscopy workflow provided geological evidence that CH_4-H_2-rich fluids, generated during serpentinization at forearc depths, can accumulate and induce brittle failure in strong rocks by reaching supralithostatic pressures. Thermodynamic modeling further shows that these fluids overpressurize more readily than CO_2-rich counterparts, suggesting a key mechanism for transporting deep Earth energy sources and potentially triggering seismicity along tectonic structures. This and other studies will be reviewed, showcasing how integrated multimodal microscopy workflows are advancing geoscientific research by addressing the complexity of natural and engineered systems.

Giuntoli F. et al. (2024) - Methane-hydrogen-rich fluid migration may trigger seismic failure in subduction zones at forearc depths. Nature Communications, 15.1, 480, https://doi.org/10.1038/s41467-023-44641-w.

On the societal relevance of economic geology

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Keywords: critical metals, mineral exploration, sustainable mining.

Exploitation of minerals and rocks was essential to early humans, the rise of ancient civilisations and the agricultural and industrial revolutions. Some mineral deposits are of such immense value that they influenced the economic and political development of entire sub-continents (e.g. Bushveld Complex and Witwatersrand gold fields in Southern Africa). Mining also causes environmental degradation, and competition over minerals often led to conflict and war. Because minerals are key to the green energy transition, global competition for their exploitation is currently intensifying again. The EU introduced a range of policies to enhance internal exploration and mining and to become less dependent on imports of so-called critical metals, i.e. those that are of high importance for the transition to the low-C (or net zero) society and the digital economy, and that have an elevated risk to their supply chains. In this talk, I will review predictions of future metal demand in relation to global megatrends including population growth, mineral use and climate change. I will show examples where critical metals are currently found and mined, and where potential for future discoveries exists.

The key challenge arising for the European mining and exploration sector is to maintain high standards of ethical practice and environmental sustainability to increase social acceptance for exploration and mining, thereby enabling our industries to increase internal sourcing of raw materials. In addition, there are technical challenges to overcome; Most shallow (near-surface) deposits have likely been found, discovery rates are falling, exploration expenditure and thus discovery costs increase, and depth of discovery increases. Furthermore, most exploration expenditure is still focussed on gold, arguably of lesser societal importance than many other metals. Also, volatility in commodity prices renders investment in mineral exploration and mining relatively risky. This restricts investment in the minerals sector from major wealth funds, with particularly negative implications for the junior exploration sector.

What other options exist to secure future raw materials supply? It has been suggested that increased recycling rates may require less mining in the future. However, while recycling is important for some commodities, e.g. steel, it is currently highly inefficient for most metals. At the same time, hopes to significantly reduce global metal consumption appear unrealistic as long as living standards remain highly unequal across the globe. On a more optimistic note, many countries and areas remain underexplored for minerals, offering opportunities for significant discoveries, particularly at depths exceeding a few 100m. Also, exploration and mining are becoming more efficient. Our understanding of ore forming processes is improving, as are geophysical and geochemical techniques. Prospectivity models based on the minerals system approach combine mappable exploration criteria on GIS platforms and use machine learning techniques to identify prospective tracts. Advances in AI will ensure that these become more efficient, particularly as several key resource countries (e.g., Australia, Finland, Canada) provide large open access geo-databases.

Planetary explorers: from Earth to future missions to the Moon and Mars

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Keywords: Planetary Science, Geology, exploration.

With the upcoming Artemis missions approaching, the return of humans to the Moon offers new research perspectives for understanding the origin of our planet, turning humanity's gaze towards Mars and even more distant planetary objects. Astronauts will be the protagonists of new planetary explorations in support of scientific research. In the coming decades, planetary geology will play a fundamental role in the collection of new samples and crucial information. Luca Parmitano, an astronaut with the European Space Agency, will share his vision of planet Earth from space, looking towards new frontiers. Through ESA CAVES and PANGAEA training, which takes place at various sites across Europe, astronauts from different agencies can get a first-hand look at the main scientific questions that remain unanswered in the exploration of the Moon. Astronauts will become the trusted eyes and arms of scientists on Earth, and their explorations will open new, countless chapters of knowledge. On a fragile planet, where humans must find a balance with nature, geological research and space exploration remain fundamental building blocks for the advancement of knowledge.

Investigating reaction gas choices for measuring Ca using MS/MS MC-ICP-MS

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Keywords: MS/MS MC-ICP-MS, Ca isotopes, collision/reaction cell.

High precision measurements of the Ca isotope system have always been challenging, due to the wide range of natural abundances for its six naturally occurring nuclides and the high number of potential interferences. Most obviously for those wishing to use multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) for Ca isotopic measurements is the isobaric overlap between $^{40}Ca^{+}$ and $^{40}Ar^{+}$, the single largest component of the ICP. MC-ICP-MS has for some time been used to measure ^{42}Ca – ^{48}Ca; but it is only in the last few years, with the re-introduction of collision/reaction cell technology to MC-ICP-MS, that it has been possible to report $\delta^{44/40}Ca$ with MC-ICP-MS, instead of a double spike Thermal Ionization Mass Spectrometry (TIMS) method. The addition of H_2 gas (alongside He) to the collision/reaction cell neutralizes the $^{40}Ar^{+}$ ions to $^{40}Ar^{0}$, allowing the $^{40}Ca^{+}$ to be measured interference free.

However, there is another potential mechanism to measure $^{40}Ca^{+}$ free from $^{40}Ar^{+}$ with a MC-ICP-MS. Like its fellow alkaline earth element Sr[4], Ca^{+} ions readily react with SF_6 in a collision/reaction cell to form CaF^{+}. SF_6 has the potential to eliminate not only the $^{40}Ar^{+}$ interference on $^{40}Ca^{+}$, but also the interference of $^{88}Sr^{++}$ on $^{44}Ca^{+}$. This opens the possibility of measuring high precision Ca isotopic ratios in-situ for solid samples via laser ablation MC-ICP-MS. Here we report our investigations into using SF_6 as a reaction gas for high-precision calcium isotopic ratio measurements with a Thermo Scientific™ Neoma™ MS/MS MC-ICP-MS for both solution and solid samples.

Chemical Imaging and molecular spectroscopy: future is now

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Keywords: molecular spectroscopy, chemical imaging, spectrometers.

Molecular spectroscopy is an important analytical area with wide impact and extent. In this field, Raman and Infrared spectroscopies are powerful and complementary techniques, with an extensive use spanning from biomedical, pharmaceutical and material sciences, to name a few.

In last decades applications related to Geological, Mineral and Art samples have become more and more demanding about several topics, like the possibility to perform *in situ* analysis of organics and inorganics in an easy way with a non invasive and non destructive approach and the possibility to get precise information on micro-scale of layered materials when it is possible to have a sample to be analysed into the laboratory.

The request per the capability to perform chemical imaging on large areas (keeping the high lateral resolution) is continuously increasing.

Today all the latest technologies (both hardware and software) have been applied by Bruker to all the Raman Spectrometers, both for portable and *in lab* instrumentations, both for dispersive and FT solutions, showing a unique portfolio on the market.

So, latest innovations will be presented in terms of commercial products, with the state of the art compromise between sensitivity and effective usability. In particular, the unpredictable capability to perform large Raman Chemical Images, on centimeters scale, will be shown.

Finally, also the amazing performances in IR imaging, when using FTIR with FPA and QCL as infrared source, will be shown for the first time in an organic way.

Ocean and climate: thirty years of multi-scale and interdisciplinary research

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Keywords: ocean and climate, Atlantic Meridional Overturning Circulation (AMOC), heat and CO_2 absorption.

The ocean plays a central role in regulating Earth's climate, absorbing approximately 90% of the excess heat and 25% of the CO_2 produced by human activities. This buffering capacity depends on a complex set of physical processes operating across a wide range of spatial and temporal scales—from large-scale circulation to small-scale eddies and fronts—that are often unresolved in climate models.

These processes, together with air–sea interactions, are critical in controlling the uptake and redistribution of heat and carbon within the ocean. The Atlantic Meridional Overturning Circulation (AMOC), for instance, is a key component of the global climate system, yet recent observations reveal a much richer and more variable behavior than what is simulated by current models—likely due in part to the lack of representation of fine-scale dynamics.

In this talk, I will discuss how the integration of multi-scale observations, high-resolution modeling, and new theoretical frameworks is essential to improve our understanding and prediction of climate evolution in a rapidly changing world.

The Anthropocene: geological signals of planetary change

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Keywords: Anthropocene, human impact, stratigraphy.

Human civilization has developed amid the relatively stability of climate and sea level, and the diverse biosphere of, the 11.7 millenia of the Holocene Epoch: the latest of many interglacial phases of the Quaternary Ice Age, and the one that shaped the world we live in.

The growth of industrialized human civilization, especially since the mid-20th century, has now put that stability into question. With the accompanying sharp rise in human numbers, energy use, technological production and globalization, have come sharp and large-scale changes to landscape, biosphere and climate. These unprecedented changes have led to the suggestion that we are now living through the beginning of a new epoch, the Anthropocene: an interval of geological time dominated by overwhelming human impacts. The term was proposed little more than two decades ago by Paul Crutzen, the Nobel Prize-winning atmospheric chemist (Crutzen, 2002), and has since been widely used – and sharply debated.

Formalization of the Anthropocene on the Geological Time Scale was proposed by the Anthropocene Working Group (Waters et al., 2024) though subsequently rejected by the International Commission on Stratigraphy. But the term and concept continue to be used (Zalasiewicz et al., 2024) and its processes are, in reality, changing the geology of our planet, bringing in changes that are significant in a deep time perspective (Syvitski et al., 2020). These include physical changes most strikingly represented by the explosive growth of the 'urban stratum': the refashioning of sand, clay and limestone into our buildings, foundations and transport systems. Biological changes include the ongoing mass extinction event and the effect of invasive species, while human-made 'anthroturbation' is as extraordinary as anything in the fossil record. Chemical changes include the reshaping of the Earth's natural carbon, phosphorus and nitrogen cycles, with their associated climate and biological impacts. Indeed, some of the planetary developments, such as the rapid growth of the technosphere – *inter alia* to now outweigh the biosphere – are wholly new within Earth's 4.5 billion-year history.

The combined transformation is of a scale to leave a signal, in strata now forming, that will persist for many millions of years, and that have already taken the planet outside of the baseline conditions of the Holocene Epoch, and in several respects out of those of the Quaternary Ice Ages as a whole. The continuing, rapidly growing departure from Holocene conditions means the Anthropocene cannot help but remain a key concept for present and future generations of geoscientists, and more widely for interdisciplinary study of an Earth System undergoing transition.

Crutzen P.J. (2002) - Geology of mankind. Nature, 415, 23, https://doi.org/10.1007/978-3-319-27460-7_10.

Syvitsk J. et al. (2020) - Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch. Commun. Earth Environ., 1, 32, https://doi.org/10.1038/s43247-020-00029-y.

Waters C.N. et al. (2024) - Executive Summary. The Anthropocene Epoch and Crawfordian Age: proposals by the Anthropocene Working Group. EarthArXiv, https://doi.org/10.31223/X5VH70.

Zalasiewicz J. et al. (2024) - What should the Anthropocene mean? Nature, 632, 980-984.

S1.

Shaping mantle heterogeneity through field observations, experiments and modeling

CONVENERS & CHAIRPERSONS

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Inefficient mixing of heterogeneous melts below the fast-spreading East Pacific Rise

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Keywords: melt aggregation, Sr-Nf-Hf *in situ* isotopic analyses, compositional heterogeneity.

At mid-ocean ridges, melts formed during adiabatic melting of a heterogeneous mantle migrate upwards and ultimately crystallize the oceanic crust. Lower crustal gabbros represent the first crystallization products of these melts and the processes involved in the accretion of the lowermost crust drive the chemical evolution of the magmas forming two thirds of Earth's surface. Yet, the complex processes accompanying magmatic accretion, the compositional variability of their mantle source and the progressive aggregation of heterogeneous melts during extraction are to date poorly constrained. Here, we provide a detailed petrochemical characterization of the primitive lower gabbroic crust formed at the East Pacific Rise and exposed at Hess Deep. There, oceanic accretion is driven by *in situ* crystallization in the lowermost gabbroic layers, followed by upward reactive percolation of melts towards shallower sections (Basch et al., 2024). We show that *in situ* isotopic analyses of single clinopyroxene and plagioclase crystals in gabbros formed at the East Pacific Rise retain substantially greater Sr-Nd-Hf isotopic heterogeneity than basalts erupted along the fast-spreading ridge. This implies that melt aggregation during migration through the upper mantle and lower crust is inefficient, even at magmatically productive spreading ridges; efficient melt mixing likely occurs in the overlying axial melt lens only (Basch et al., 2025). Local isotopic heterogeneity of Hess Deep gabbros indicates incomplete mixing of primary melts produced from variably depleted peridotites and oceanic crust recycled at least 1.5 billion years ago. Conversely to other East Pacific Rise ridge sections, recycled sediments are not involved in the formation of melts in Hess Deep subridge mantle. The isotopic heterogeneity recorded in lower gabbros further substantiates that basalt compositions reflect only part of the compositional spectrum of melts passing through the ridge plumbing system.

Basch V. et al. (2024) - Accretion of the lower oceanic crust at fast-spreading ridges: Insights from Hess Deep (East Pacific Rise, IODP Expedition 345). J. Petrol., 65, https://doi.org/10.1093/petrology/egae048.

Basch V. et al. (2025) - Inefficient melt mixing below a fast-spreading ridge revealed by Hess Deep lower gabbros (ODP Leg 147 and IODP Expedition 345). Sci. Adv., 11, https://doi.org/10.1126/sciadv.adu2044.

Geochemical variability of melts impregnating residual peridotite in the Oman Ophiolite (Wadi Tayin Massif)

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Keywords: lithospheric mantle, plagioclase stability field, impregnating melts geochemistry.

The oceanic lithosphere exposed in the Oman ophiolite preserves a complex record of melt migration and magmatic accretion, involving melts with different geochemical signatures. Despite several studies have investigated the magmatic features within the Moho Transition Zone (MTZ) and the layered crust, detailed microstructural and geochemical investigations on melt percolation and impregnation processes in the Oman mantle harzburgite section are still very limited. This study focuses on plagioclase-bearing impregnation structures recorded in the Wadi Tayin mantle section, aiming to characterize the geochemical affinity of melts migrating throughout the uppermost lithospheric mantle and their relationships with the overlying MTZ and crustal sequence. Studied impregnation structures are composed of various modal proportions of magmatic and interstitial plagioclase + clinopyroxene + orthopyroxene that crystallize in a harzburgitic or dunitic host rock, forming impregnated harzburgite and troctolite, respectively. In the harzburgitic domain, melts form impregnation-related trails or veinlets, whereas in dunite their percolation leads to the formation of troctolitic pods or lenses enclosed within the harzburgitic wall rock. The Mg# value (Mg/(Mg+Fe) × 100 mol%) of magmatic clinopyroxene and the An% content (Ca/(Ca+Na) × 100 mol%) of plagioclase exhibit a positive correlation ranging between 90.6% - 92.9% and 86.4% - 98%, respectively. These values point to a generally depleted geochemical affinity of all impregnating melts. Trace element patterns of melts calculated in equilibrium with clinopyroxene across different lithotypes show variable Light Rare Earth Elements (L-REE) depletion and Zr/Hf elemental ratios. Specifically, some calculated melts show La/Yb (0.63-1.34) and Zr/Hf (34.5-64.1) ratios comparable to the Oman V1/Geotimes lava and the Oman oceanic gabbros, independently of mineral modal contents. By contrast, other calculated melts are characterized by significantly lower La/Yb (0.07-0.26) and Zr/Hf ratios (12.9-24.3), indicating a strong depletion in highly incompatible trace elements. The observed chemical heterogeneity of impregnating melts could reflect different extents of reaction between MORB-like melts and the peridotitic upper mantle, and/or the occurrence of unaggregated melts characterized by primary depletion in incompatible trace elements. Understanding such processes is key to reconstructing the latest magmatic events recorded in the upper mantle harzburgite, and to assessing the role of migrating melts in the geochemical budget of the oceanic crust. This contributes a crucial perspective to the complex accretional history of the Oman oceanic lithosphere.

An ancient enrichment in the Atlantic mantle recorded by Hf and Nd isotopes in abyssal peridotites from the 15° N 20' fracture zone

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Keywords: peridotites, Hf-Nd isotopes, IODP.

Abyssal peridotites allow valuable insights into small scale mantle heterogeneities that are lost in the record provided by oceanic basalts (e.g., Sanfilippo et al., 2024). To address this issue further, we report trace element concentrations and Sr, Nd, Hf isotope compositions for mantle peridotites and gabbroic rocks collected from the 15° N 20' fracture zone in the Atlantic during ODP Expedition 209. The peridotites, previously described by Paulick et al. (2006), are highly serpentinized and consist of former harzburgites and dunites with variable trace element enrichments and alteration styles. Isotope and trace element analyses were conducted on bulk rock samples and leachates/residues obtained through HCl leaching experiments.

Most samples exhibit ranges for ε_{Hf} (+15 to +20) and ε_{Nd} (+6 to +11) typical for the depleted upper mantle. However, two dunite bulk samples display anomalously unradiogenic Hf ($\varepsilon_{Hf} \approx -18$) while retaining ε_{Nd} values similar to the other samples. Leachate residues from these samples showed similar unradiogenic Hf and, in one case, also unradiogenic Nd ($\varepsilon_{Nd} \approx -12$). These findings suggest the presence of an ancient enriched component in the oceanic mantle with a crustal or melt-like signature. Such a signature was later modified by metasomatic processes that enriched the rocks in rare earth elements (REEs), especially light REEs, but without achieving full chemical equilibrium at the bulk scale. This study highlights the heterogeneity of the oceanic lithosphere, which contains ancient domains with different Hf-Nd signature, from ultra-depleted (e.g., Sanfilippo et al., 2024) to enriched.

Acnowledgment: The work is part of the WP7.1 ECORD ITINERIS project, EU – Next Generation EU.

Paulick H. et al. (2006) - Geochemistry of abyssal peridotites (Mid-Atlantic Ridge, 15°20′N, ODP Leg 209): Implications for fluid/rock interaction in slow spreading environments. Chem. Geol., 234, 179-210, https://doi.org/10.1016/j.chemgeo.2006.04.011.

Sanfilippo A. et al. (2024) - Upwelling of melt-depleted mantle under Iceland. Nat. Geosci., 17, 1046-1052, https://doi.org/10.1038/s41561-024-01532-z.

Enriched heterogeneities in MORB source are not inherited from hotspots

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Keywords: alkaline MORB, Mid Ocean Ridge, mantle heterogeneity.

The Earth's upper mantle source of Mid Ocean Ridge Basalts (MORB) is progressively revealing a short scale lithological variability. Traditionally, geochemists have viewed the MORB source to be a relatively uniform reservoir perturbed by hot spots, with geochemical anomalies attributed to the influence of hot spots distinct mantle components that serve as a compositional reference frame. In this study, we shift the focus to cold regions of Mid-Ocean Ridges, particularly the Eastern Romanche Ridge-Transform Intersection (ERRTI) in the Equatorial Mid-Atlantic Ridge (Grenet et al., 2025). In this low temperature setting, reduced mantle melting allows individual lithological components to be extracted separately, revealing that isotopically-inferred heterogeneities are hosted in distinct units with relatively low solidus temperatures (Brunelli et al., 2025). At least five such components have been identified. Notably, some basalts display isotopic and incompatible element signatures derived from shallow melting of garnet-bearing fertile lithologies generating alkaline potassium and sodic rich basalts. Their isotopic composition does not match any of the plume-inferred isotopic systematic suggesting contribution from recycled subduction components stirred in the global mantle convection. This fine-scale lithological variability and the presence of such signatures in a non–hot spot setting challenges conventional models and highlights the need to revise the rheological, geochemical, and petrological understanding of the MORB source.

Brunelli D. et al. (2025) - Large melt diversity at a mid-ocean ridge thermal low. Sci. Adv., 11, eadv4654, https://www.science.org/doi/10.1126/sciadv.adv4654.

Grenet L. et al. (2025) - A deep dive into a ridge-transform fault intersection: Volcano-tectonic relationships in an enhanced cold-edge effect at the Romanche fracture zone. J. Geophys. Res., Solid Earth, 130(4), https://doi.org/10.1029/2024JB030688.

In-situ boron isotopes reveal recycling processes in the Early Earth

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Keywords: boron isotopes, Early Earth, LA-MC-ICP-MS.

The evolution of Earth during the Archean Eon (about 4.0 to 2.5 Ga ago) was marked by intense geological activity leading to planetary differentiation. During this time, Earth's surface transitioned from a molten state to a more stable, albeit dynamic, proto crust. One of the defining processes of the Early Earth evolution was crustal recycling, where early continental and oceanic crust was repeatedly formed, deformed, and re-melted due to high mantle temperatures associated with vigorous convection. Unlike modern-style plate tectonics, Archean crustal recycling, if any, likely involved smaller, short-lived tectonic plates and proto-subduction processes. Understanding these early mechanisms is crucial for reconstructing the formation of Earth's first stable continent and the development of its long-term geochemical cycles. The transition from a stagnant lid to modern-style plate tectonics is an unresolved, long-standing historical debate. Here, we try to unravel this knowledge gap presenting the first *in-situ* boron isotope ($\delta^{11}B$) investigation in olivine from the Narssaq ultramafic body (SW Greenland), one of the most extensive studied Eaoarchean ultramafic section (e.g., van de Locht et al., 2020; Zhang & Szilas, 2024). Variations in $\delta^{11}B$ signatures in olivine can provide valuable insights into the recycling of surficial materials in the Earth's mantle. Boron isotope measurements were carried out at the Geochemistry laboratory of the University of Milan (GL@M) using LA-MC-ICP-MS. Olivine from the Narssaq ultramafic body display significant enrichment in B ranging from 2 to 8 µg/g, uncommon for mantle-derived olivine (usually << 1 µg/g, Kent & Rossman, 2002). Their measured $\delta^{11}B$ signatures show *ca.* 15‰ variability and are dissimilar to the mantle signature of -7.1 ± 0.9‰ (Marschall et al., 2017). The elevated B contents and wide $\delta^{11}B$ variability in Narssaq olivine suggest that surficial or crustal materials were recycled into the mantle as early as the Eoarchean. Our preliminary results support models of plate tectonic-like processes or subduction-related recycling during early Earth's evolution.

Kent A.J.R. & Rossman G.R. (2002) - Hydrogen, lithium, and boron in mantle-derived olivine: The role of coupled substitutions. Am. Mineral., 87(10), 1432-1436, https://doi.org/10.2138/am-2002-1020.

Marschall H. et al. (2017) - The boron and lithium isotopic composition of mid-ocean ridge basalts and the mantle. Geochim. Cosmochim. Acta, 207, 102-138, https://doi.org/10.1016/j.gca.2017.03.028.

Van de Löcht J. et al. (2020) - Preservation of Eoarchean mantle processes in ~ 3.8 Ga peridotite enclaves in the Itsaq Gneiss Complex, southern West Greenland. Geochim. Cosmochim. Acta, 280, 1-25, https://doi.org/10.1016/j.gca.2020.03.043.

Zhang L. & Szilas K. (2024) - Eoarchean ultramafic rocks represent crustal cumulates: a case study of the Narssaq ultramafic body, southern West Greenland. Earth Planet. Sci. Letters, 625, 118508, https://doi.org/10.1016/j.epsl.2023.118508.

Multiple mantle sources in continental alkaline magmatism: a case study from the Cenozoic volcanism in Jordan

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Keywords: alkaline magmatism, mantle heterogeneity, trace elements.

The continental rift system spanning from the Afar triple junction to the Red Sea and the Dead Sea Transform produced widespread magmatism distributed from the Oligocene to the Quaternary. This volcanic activity formed one of the largest alkali basalt provinces on Earth scattered from the Afar region to Arabia and Levant. The volcanic activity was also abundant in Jordan along the Dead Sea Transform Zone, suggesting a link between volcanism and transform tectonics. This study presents new major, trace element data and isotopic compositions on new samples collected from small lava-fields scattered along the Dead-Sea Transform Fault, in Jordan. The samples are high MgO basalts and basanites, with basanites being significantly more enriched in TiO_2 and highly incompatible trace elements (e.g., Cs, Rb, Ba, Th, U, Nb, Ta, LREE). Basanites have high contents of HFS elements and extremely fractionated heavy rare earth elements with chondrite-normalized Sm/Yb ratios up to 12, significantly higher than most of the synchronous Cenozoic Arabian alkaline magmas. Notably, these lavas are distinct from the volcanics forming the large neighboring Harrat Ash Shaam. Overall, the studied rocks show negligible evidence of contamination by either upper or lower continental crust and display incompatible trace element patterns and specific trace element ratios (e.g., low Rb/Nb, Rb/Th) similar to those of Ocean Island Basalts having an HIMU signature although isotopic composition are not HIMU-like. Covariations in Dy/Yb vs. La/Yb indicates that the erupted magmas were formed by mixing melts from lithospheric sources, with small-degree melts formed by garnet-bearing asthenospheric source. Moreover, the extremely low Rb/Sr ratio and K negative anomaly, together with the relatively high Nb/Ta of some samples, indicate the contribution of another distinct component, which points toward the average composition of East African Rift carbonatites. This carbonatitic component was possibly preserved within the subcontinental lithospheric mantle, then melted and mixed with the ascending asthenospheric magmas due to lithospheric thinning in time of rifting.

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Olivine trace element content in spinel to garnet peridotite xenoliths from Udachnaya-East (Siberia) and the chemical log of the sub-cratonic lithospheric mantle

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Keywords: olivine trace elements, spinel and garnet peridotite, sub-cratonic lithospheric mantle.

The chemical composition of olivine is increasingly used to explore a wide range of processes within the Earth's mantle and volcanic plumbing systems, with particular focus on the evolution of alkaline-carbonatitic and kimberlitic melts, and their associated diamond potential. Yet, the trace element-poor nature of olivine in mantle-derived peridotites, and especially the low concentration of incompatible trace elements, is analytically challenging to acquire. The chemical characterization of olivine in mantle peridotites is often limited to low-current major element analyses by EPMA, while a fuller characterization of olivine trace element compositions allows tracing the *T*-*P*-fO_2 conditions, nature and metasomatic modification of the lithospheric mantle.

Using routine, high-precision EPMA and LA-ICP-MS analyses and building on the pioneering works by De Hoog et al. (2010) and Bussweiler et al. (2017), we provide the first comprehensive dataset on olivine chemical composition in spinel, spinel-garnet and garnet peridotite xenoliths sampled through an entire lithospheric mantle section by the Udachnaya-East kimberlite (Siberian craton). Combined with thermobarometric modelling, bulk-rock composition and major element composition of the coexisting minerals, this allows exploring the utility of olivine as a recorder of processes in the lithospheric mantle.

Our results show that olivine composition is variably controlled by a combination of *T*-*P*-fO_2 conditions, and melt-related enrichment, and faithfully discriminates between three groups of xenoliths:

- refractory, coarse granular peridotites equilibrated at low-*T* (770-1000 °C) are generally composed of olivine depleted in all trace elements;
- fertile to refertilized garnet-bearing rocks equilibrated at high-*T* (1180-1360 °C) and *P* = 5-6 GPa, enriched in all basaltic components, which record earlier significant addition of HFSE, Fe, Ca, Al and P at the base of the Siberian lithosphere;
- metasomatically-derived wehrlites and dunites, which equilibrated at low-*T* but preserve selective trace element enrichment in olivine.

Integrated to literature data, our results enabled also to discuss the applicability of diagrams used for discrimination between spinel- and garnet-bearing peridotitic olivine, thus improving our knowledge of the nature and evolution of the lithospheric mantle and the provenance of the xenocryst cargo in kimberlites.

Bussweiler Y. et al. (2017) - The aluminum-in-olivine thermometer for mantle peridotites - experimental versus empirical calibration and potential applications. Lithos, 272, 301-314, https://doi.org/10.1016/j.lithos.2016.12.015.

De Hoog J.C. et al. (2010) - Trace-element geochemistry of mantle olivine and application to mantle petrogenesis and geothermobarometry. Chem. Geol., 270(1-4), 196-215, https://doi.org/10.1016/j.chemgeo.2009.11.017.

Structural evolution of carbonate glass at deep mantle pressures: implications for carbon storage and mantle dynamics

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Keywords: carbon cycle, extreme conditions, synchrotron.

Carbonatites, mantle-derived carbonate-rich magmas, are key players in Earth's deep carbon cycle, yet their role at lower mantle depths remains poorly constrained. We investigate the structural evolution of a simple C-rich glass, $K_2Mg(CO_3)_2$, as a proxy for carbonate melts under deep mantle conditions. Using X-ray diffraction, X-ray Raman scattering, and *ab initio* simulations, we track its behavior up to 115 GPa. Our results reveal a progressive densification up to ~33 GPa, followed by a significant structural reorganization between ~40 and 112 GPa, marked by a pressure-induced transition from sp^2 to sp^3 hybridized carbon. This transformation corresponds to the conversion of planar $^{[3]}(CO_3)^{2-}$ units into tetrahedral $^{[4]}(CO4)^{4-}$ groups, accompanied by changes in oxygen coordination and the emergence of a three-dimensional carbonate network. These findings support the presence of polymerized, viscous, carbon-rich silicate melts in the lowermost mantle, potentially hosted in Large Low Velocity Provinces (LLVPs). Such melts could serve as long-term carbon reservoirs and feed the carbon-rich magmatism observed at intraplate hotspots like Hawaii and Samoa. Our study provides a structural mechanism linking deep carbon storage to surface emissions, highlighting the need for further exploration of carbonate and carbon-rich silicate melts under extreme conditions.

Mantle refertilization via melt–harzburgite interaction: an experimental study at 1–2 GPa

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Keywords: melt-peridotite reaction, trace elements, experimental petrology.

Refractory peridotites, after undergoing partial melting, can be further modified through interaction with migrating MORB-type melts at the flanks of oceanic melting regions. These processes occur prior to their incorporation into the lithospheric mantle and significantly influence the chemical and isotopic evolution of large portions of the oceanic upper mantle. While recent experimental studies have demonstrated that trace elements, especially Rare Earth Elements (REEs), can be rapidly redistributed in mantle clinopyroxene via dissolution and reprecipitation processes (Borghini et al., 2023), the trace element redistribution in mineral phases of orthopyroxene-bearing mantle rocks still remains to be constrained. This work experimentally investigates the interactions between Enriched-MORB melt and harzburgite under conditions representative of the oceanic asthenosphere-lithosphere boundary (1–2 GPa; 1150–1400 °C). We present the results of reaction (isothermal and cooling) experiments starting from a modeled harzburgite, made by depleted orthopyroxene (La_N/Yb_N = 0.004), San Carlos olivine (Fo_{90}), homogeneously mixed to tholeiitic basaltic glass (X_{Mg} = 0.60, Na_2O = 3.48 wt%, K_2O = 0.81 wt%) with E-MORB signature (La_N/Yb_N = 5.39). High-temperature isothermal runs (1200-1350 °C) simulate transient melt percolation and resulted mostly in orthopyroxene dissolution and olivine dissolution and reprecipitation. Experiments cooled to 1150-1200 °C experienced reactive melt crystallization that leads to clinopyroxene and orthopyroxene precipitation, associated with garnet at 2 GPa or plagioclase at 1 GPa. After the reaction, rims of partially dissolved orthopyroxene and newly crystallized orthopyroxene tend to acquire high TiO_2 and Al_2O_3 and low Cr_2O_3 contents than initial orthopyroxene. Olivine from high temperature runs has high X_{Mg} (up to 0.95), high Ca, and low Ni, while cooling experiments results in lower X_{Mg} (up to 0.84), moderate Ca, and variable Ni contents. Several rims of orthopyroxenes relicts show selective LREE enrichment likely due to REE diffusion during the reaction. Newly formed orthopyroxenes exhibit LREE enrichments ($La_{N/}Sm_N$ = 0.19-1.38) with respect to the initial orthopyroxene ($La_{N/}Sm_N$ = 0.04). Accordingly, such extreme enrichments in orthopyroxenes have been documented in abyssal peridotites and ascribed to metasomatism by infiltration of moderately evolved melts. Clinopyroxenes have high convex upward LREE patterns with MREE/HREE fractionation more marked than in orthopyroxene-free assemblages. Reacted glasses show slight LREE/HREE fractionation and high absolute REEs contents at increasing extent of the interstitial melt crystallization. This study also provides "reaction" partitioning coefficients (Kd_{REE} = $C_{REEsolid}/C_{REEliquid}$), offering new quantitative constraints on trace element redistribution in mantle minerals during reactive melt percolation of basaltic melts.

Borghini G. et al. (2023) - Fast REE re distribution in mantle clinopyroxene via reactive melt infiltration. Geochem. Persp. Letters, 26, 40-44, https://doi.org/10.7185/geochemlet.2323.

Distinct mantle metasomatic agents inferred from trace element and H_2O contents of diamond-hosted mineral inclusions

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Keywords: metasomatism, diamonds, inclusions.

Metasomatic processes play a key role in the evolution and dynamics of the Earth's interior. In these processes, different types of fluid/melts interact with mantle rocks, changing their mineralogical, geochemical and isotopic composition, as well as their physical properties. For this reason, so far, many studies have focused on understanding metasomatic processes by studying trace elements in a variety of mantle xenoliths from different geological settings and localities.

Diamonds, being a product of metasomatic reactions in the deep mantle, have been extensively studied to understand the metasomatic agents and processes responsible for their formation. In this regard, special attention has been given to fluid inclusions hosted in fibrous diamonds, which, however, are thought to be strictly related to kimberlite eruption and therefore may not be representative of the ambient lithospheric mantle where monocrystalline diamonds form. A large body of literature has also focused on studying the trace element concentration and patterns of mineral inclusions in lithospheric diamonds, reconstructing a complex metasomatic history.

It was recently suggested that extremely fast diffusion of H in common rock-forming minerals would allow the H_2O content of diamond-hosted mineral inclusions to equilibrate with that of the diamond forming agent during diamond formation. Consequently, studying the H_2O content of diamond-hosted mineral inclusions, coupled with trace elements data, can further constrain mantle metasomatic processes forming lithospheric diamonds. As of today, however, H_2O and trace elements concentrations on the same diamond-hosted mineral inclusions have never been reported.

In this work we report, for the first time, the analyses of the trace elements concentration for a set of 11 diamond-hosted mineral inclusions whose H_2O content was previously measured. The suite of analyzed samples comprises clinopyroxenes and garnets (of both the peridotitic and eclogitic paragenesis) from different localities from the Kaapvaal, Siberian and North Australian cratons. The rare earth element concentrations and H_2O content was compared with all the data presently available on mantle xenoliths to observe possible similarities and differences in the metasomatic history of the samples. The results will be discussed in the context of the type and characteristics of metasomatic agents in the lithospheric mantle responsible for alteration of both diamond-hosted mineral inclusions and mantle xenoliths.

The behaviour of hydrogen in natural diamond: insights into the formation and preservation of hydrogen- and nitrogen-bearing defects

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Keywords: diamond, point defects, nitrogen and hydrogen.

Impurities in natural diamond are routinely used to investigate the types and sources of diamond-forming fluids, the effects of plastic deformation and natural irradiation, and the thermal history of diamond residence in the mantle. Although our understanding of vacancy (*V*) and nitrogen (N) defects in diamond has improved considerably, the behaviour of hydrogen (H) defects remains poorly understood and thus the full extent of geological information that can be extracted from H in diamond in still unknown. Recently, interest in the H content and isotopic composition of diamond has increased, driven by its potential as a proxy for tracing the primordial (or recycled) H_2O reservoirs from which diamond-forming fluids are sourced and for broader implications about the Earth's deep H cycle.

Despite the ubiquity of H in diamond, only a handful of H-related defects, e.g., VN_3H and VN_4H (Goss et al. 2014; Keat et al. 2024), have been rigorously identified and likely represent the *end-point* of *V*/N/H-defect aggregation that occurs during long periods of annealing in the mantle (Day et al. 2024). However, before H in diamond can be used as a viable geochemical tool, the potential for H re-equilibration with the ambient mantle and/or kimberlitic melts must be evaluated. This requires knowledge of (i) the mechanisms by which H is incorporated during diamond crystallization, (ii) how efficiently *V*/N-defects trap H to form defects and the degree to which such defects prevent diffusive loss of H, and (iii) how H-related defects aggregate with other *V*/N/H-defects during the initial stages of mantle residence.

Access to a large sample suite of extremely rare, H-bearing *Type Ib* diamonds that reflect N/H-defect aggregation states shortly after diamond formation, has resulted in the discovery of two new N/H-defects, the identities of which were determined using *ab initio* and machine-learning molecular dynamics simulations. Correlations between the N-aggregation state and the IR peak intensities for these new N/H-defects suggest they are likely the first H-bearing point defects that form in diamond, defining a *starting-point* for H in diamond. Annealing studies and additional spectroscopic analyses have allowed formulation of new *V*/N/H-aggregation sequences that are likely operative during, or immediately after, diamond crystallization. In general, our findings suggest H is strongly trapped by *V*/N-defects in diamond shortly after its incorporation thus preventing later re-equilibration via diffusive loss.

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Mineralogy and geochemistry of ultramafic xenoliths from Wallis islands: insights into mantle processes in the Southwest Pacific lithosphere

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Keywords: mantle, xenolith, South Pacific.

Wallis Island is located in the central South Pacific, between Fiji and Samoa. Its geodynamic context is dominated by intraplate volcanism; however, its relationship with the Samoa hotspot remains debated (Price et al., 2014). The island is composed of recent (< 0.5 Ma) lava flows with affinities ranging from alkaline to tholeiitic, and with associated pyroclastic rocks (Price et al., 1991). Here, we present a mineralogical and geochemical study on a suite of ultramafic xenoliths enclosed within pyroclastic tuffs. The xenoliths include dunites and websterites. The dunites are predominantly composed of olivine (Fo contents = 88-90 mol%), and Cr-rich spinel (Cr# = 73-80); trace amounts of Cpx were observed in a dunite sample. Mineral chemistry supports the hypothesis that the dunites formed as cumulates from near-primitive basaltic magmas.

The websterites consist of approximately equal proportions of Opx (~50 vol%) and Cpx (~45 vol%), with minor Fe-rich olivine (Fo_{79-84}) occurring interstitially or as inclusions within Opx. Al-rich, Cr-poor spinel occurs as tiny inclusions within clinopyroxene. Both pyroxenes exhibit extensive mutual exsolution textures. Cpx is characterized by elevated Al_2O_3 contents (7.69–8.52 wt%), moderate TiO_2 (0.43–0.80 wt%), and Na_2O (0.93–1.20 wt%). Using the model of Wood and Blundy (1997), equilibrium melts calculated from Cpx cores yield Mg# values ~ 50, suggesting crystallization from a moderately evolved melt. Cpx displays flat to slightly convex-upward REE patterns with fractionated heavy REEs. Calculated melts in equilibrium with Cpx are enriched in light REEs, with variable La/Yb fractionation (La_N/Yb_N = 3-12). Application of conventional pyroxene thermometry yield high equilibration temperatures (1070-1150 °C). The formation of Cpx + Opx (+ Ol + Spl), in the absence of plagioclase, suggests that the websterite crystallization occurred at relatively high pressures (> 9 kbar; Elthon, 1993). Our findings suggest that the dunites and websterite xenoliths represent cumulates from primitive to evolved melts within a relatively deep section of the Pacific oceanic lithosphere.

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Cenozoic dynamics and anorogenic volcanism of the Central Mediterranean and NE Asia: insights from geodynamic modelling

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Keywords: geodynamics, intraplate volcanism, numerical modeling.

The Cenozoic tectonic and magmatic evolution of the Central Mediterranean and NE Asia and their first-order present-day structure have been relatively well constrained by abundant geological and geophysical data. Yet, several uncertainties persist about the mechanisms that led to (i) the present-day surface morphology and deep slab geometry, and to (ii) a complex magmatic history characterized by several anorogenic events. With this respect, over the past few years new geodynamic and seismological modelling techniques have been combined to reproduce the recent large-scale evolution of these tectonic settings.

For the Central Mediterranean, the geodynamic simulations were designed and calibrated according to paleogeographic-tectonic reconstructions and seismological observations available in the literature. It is found that, although the opening of back-arc extensional basins in response to the retreat of the Ionian slab is a common feature in all models, structural heterogeneities within the Adria plate and/or the geometry of its Tyrrhenian passive margin profoundly affect the segmentation of the subducting slab and the amount of Ionian trench retreat. Subduction of continental passive margin material occurs along the teared margins of the slabs (Fig. 1 bottom). The roll-back of the Ionian slab induces horizontal flow of the asthenosphere around the rigid lithospheric portions and toward the mantle wedge in response to pressure exerted by its mid-to-late Cenozoic horizontal motion. The descending lithosphere is compensated by mantle return flow upwelling from the Mantle Transition Zone (MTZ), especially around the tip of the stagnating slab.

We show that when small amounts of water ($\leq$ 0.3 wt%) are present in Nominally Anhydrous Minerals (NAMs) of the MTZ, the exhumation of the wet MTZ at upper mantle depths causes widespread partial melting, which can explain part of the observed intraplate (anorogenic) volcanism.

A similar, but 2D, model applied to the Cenozoic evolution of the Pacific plate subduction under Japan demonstrate that this process can be responsible for the formation of anorogenic magmatism offshore of the Japan trench (petit-spots) and in the Korean peninsula and mainland China (Yang & Faccenda, 2020).

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Experimental insights into the distribution of hydrous carbonate melts in dunite

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Keywords: carbonatitic melts, dihedral angles, textural development.

Carbonate melts are widely recognized as key metasomatic agents in the Earth's mantle. Their physical properties influence their mobility from the source region to shallower depths, playing a crucial role in the long-term carbon cycle. The grain-scale distribution of partial melts is essential for understanding mass transport in these magmatic systems. Previous studies have investigated the geometry and connectivity of intergranular liquids by measuring dihedral angles (θ). Carbonate melts in contact with olivine develop θ values of approximately 28°–30° (Hunter & McEnzie, 1989; Watson et al., 1990), significantly lower than those observed for silicate melts in contact with other silicate minerals. This suggests that, even at very low melt fractions, carbonate melts – characterized by low density and viscosity – remain interconnected within a dunite matrix, ensuring high mobility under mantle conditions. While natural carbonatitic melts are complex systems dominated by C–O–H species, most previous research has focused on anhydrous model systems. This study aims to investigate the textural equilibrium of volatile-rich carbonate melts in a dunite matrix, considering the effects of both time and water content.

We conducted piston-cylinder experiments at 2.5 GPa and 1200 °C, with run durations ranging from 3 to 306 hours. The experiments involved juxtaposing a pre-sintered dunite rod – composed of sieved (< 64 μm) San Carlos olivine, pre-annealed at 0.8 GPa and 1200 °C – with a hydrous carbonate source of dolomitic composition (containing either 5 or 30 wt.% added water). Polyhedral olivine grains show well-developed triple junctions and evidence of crystal growth. The hydrous carbonatitic fraction is distributed as melt pockets along olivine grain boundaries and, in longer-duration experiments, as interconnected channels. The volume of liquid infiltrating the dunite matrix decreases from ~10 vol.% to ~2 vol.% over time and is lower in experiments with higher water content. Notably, the presence of water increases the apparent dihedral angle, which evolves from ~31° at 3 hours to ~41° at 300 hours, reaching nearly 50° in runs with 30 wt.% water.

The observed evolution of wetting angles mimics sintering processes in the solid matrix (German et al., 2009) and provides a likely framework for exploring melt channelization. These findings offer new insights into the mobility and interconnectivity of carbonatitic liquids in the Earth's mantle. Our experimental approach, using synthetic dunite and hydrous carbonatitic melts, highlights the influence of water and challenges previous assumptions regarding the wetting behavior of carbonatitic liquids.

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An ancient mantle component in oceanic and continental lavas

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Keywords: kimberlites; oceanic basalts; chemical geodynamics.

The Sr-Nd-Hf-Pb isotope geochemistry of ocean Island basalts can be described as a mixture of variously enriched or depleted endmembers with a common component of intermediate composition termed Focal Zone (FOZO) or C. Whereas the enriched components are widely recognized as subducted or delaminated lithospheric material, the origin of FOZO is unclear despite its central role in mantle geochemistry. FOZO might represent a relatively homogeneous mixture of subducted material and depleted mantle (Stracke et al., 2005). In alternative, the association of FOZO with primordial He isotopes (i.e. high $^{3}He/^{4}He$) was previously attributed to an ancient origin for this component (Hart et al., 1992).

In this work I will elucidate the origin of FOZO by drawing on recent compilations of the isotope geochemistry of oceanic and continental lavas, including kimberlites, augmented by constraints from petrology, high-pressure experiments, and geochronology. Kimberlites, which derive from low-degree melting of carbon-bearing peridotites in the upper convective mantle, have been consistently tapping FOZO since at least 2.1 Ga (Giuliani et al., 2021). This observation implies that FOZO is a long-lived component of Earth's mantle and not a product of plate tectonics. Extrapolation of kimberlite-based FOZO to the Hadean suggests that this component might stem from early differentiation of the silicate Earth.

Confirmation that FOZO represents a low-degree melting component comes from the composition of intraplate oceanic and continental basalts of Cenozoic age. High-Mg basalts with the highest concentrations of incompatible trace elements (Nb, Th) exclusively tap FOZO with negligible contribution of other mantle components (Cai et al., 2023). The global distribution of these basalts implies that FOZO is widespread in the convective mantle rather than being associated with thermal boundary layers such as the core-mantle boundary. These observations require that convective stirring has been unable to convectively homogenize these remnants of early Earth differentiation, which is in line with thermochemical simulations of global mantle convection (Cai et al., 2023).

While an ancient origin of FOZO seems to be consistent with an association of FOZO with elevated $^{3}He/^{4}He$ (Hart et al., 1992), a reassessment of the He isotope systematics of mantle-derived lavas clarifies this is not the case. Elevated $^{3}He/^{4}He$ are exclusively found in plume-related lavas of broadly tholeiitic composition with low concentrations of incompatible trace elements. In contrast with FOZO, these lavas are generated by high degrees of melting and extend to isotopic compositions more depleted than FOZO. The association of high $^{3}He/^{4}He$ lavas with hot plumes combined with modelling of He diffusion requires that primordial ^{3}He is delivered to the deepest mantle by exchange with either the core or magma ocean residues at the core-mantle boundary.

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Ultrapotassic and carbonatitic magmatism of the Upper Cretaceous Salitre intrusion (Alto Paranaíba Igneous Province, Brazil)

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Keywords: kamafugites, lamproites, carbonatites.

The Upper Cretaceous Salitre intrusion (~86-82 Ma) is part of the Alto Paranaíba Igneous Province (APIP), a widespread area in SE Brazil. Lamprophyre and carbonatite samples are being collected from drill holes along with a variety of other intrusive rocks (perovskite-phlogopite dunites, phlogopite-perovskite clinopyroxenites, glimmerites, phoscorites, and perovskitites). The Salitre lamprophyres can be distinguished into two distinct mineralogical assemblages. The first assemblage is characterized by olivine and phlogopite phenocrysts set in a fine-grained groundmass of clinopyroxene, apatite, phlogopite, magnetite, chromite, and perovskite, with rare titanite and schorlomite garnet. This group has a kamafugite affinity. The second has phlogopite and clinopyroxene phenocrysts in a groundmass of alkali feldspar, clinopyroxene, apatite, carbonate, and ilmenite. Zircon, baddeleyite, and wadeite are accessory minerals. This group of dikes has a lamproite affinity. Both lamprophyres are ultrabasic (SiO_2 = 33-36 wt% and 28-39 wt%), ultrapotassic (K_2O/Na_2O = 5-14 and 2-4; K_2O = 4-5 wt% and 4-6 wt%) and peralkaline (PI = 1.1-1.3 and 1.2-1.9) with variable concentrations of MgO (9-14 wt% and 6-10 wt%), REE (∑REE=500-1,300 ppm and 750-1,500 ppm) and other trace elements (Nb, Zr, Sr, Ba). The mantle sources of the Salitre lamprophyres and APIP kamafugites are likely carbonated garnet lherzolites with phlogopite veins, strongly enriched in HFSE and REE. The Salitre carbonatites have calcite as the dominant cumulus phase, and apatite, phlogopite, olivine, dolomite, pyrochlore and magnetite as intercumulus phases. Classified as calciocarbonatites (CaO = 30-53 wt%, MgO = 2-15 wt%), they are rich in REE (∑REE up to 5,300 ppm), Sr (up to 11,700 ppm) and Ba (up to 3,800 ppm). They also exhibit the K, Pb, Zr, Hf and Ti troughs of primary igneous carbonatites in primitive mantle-normalized diagrams as their O-C isotope values. Other ultramafic rocks are variably and modally enriched in olivine, clinopyroxene, phlogopite, perovskites, oxides, apatite, and carbonate. These ultramafic cumulates formed through the differential settling of these mineral phases when the Salitre magma chamber was filled with silica-poor, Ca-rich melts, rich in HFSE, REE, and volatiles. The carbonatites were likely formed through the extensive fractional crystallization of carbonate-rich magmas.

Experimental constraints on crustal assimilation: interaction of ultrabasic melts with natural marly limestones

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Keywords: ultrabasic melts, carbonates, melt assimilation.

Interaction and assimilation of crustal materials represent common processes experienced by magmas during their ascent in continental settings. The effect is usually a strong modification of the mineralogical, geochemical and isotopic composition of the original magma, coupled with an enhanced fractional crystallization. Interaction experiments conducted using natural rock samples and variable crustal lithologies under variable pressure and temperature conditions provide fundamental insights into these processes. Sedimentary SiO_2-poor to SiO_2-free (carbonated) lithologies are common crustal contaminants, but experimental constraints on their role during crustal assimilation are relatively scarce. Most of these experimental studies involve synthetic carbonates and are mainly focused on mafic to intermediate magma compositions. The few experiments carried out at crustal pressure (2 kbar) using strongly ultrabasic compositions used pure $CaCO_3$ as crustal replicate (e.g., Lustrino et al., 2022). As consequence, the behaviour of silica-poor, alkali-rich melts during crustal interaction with natural carbonated lithologies (limestones and marly limestones) remains poorly constrained.

For this reason, nine experiments were conducted using a non-end loaded piston cylinder ("QUICKpress" apparatus) at 1100, 1200, and 1300 °C and 2 kbar. The selected starting materials consist of ultrabasic and mafic lavas from the Bohemian Massif (Czech Republic and Germany), including a polzenite (i.e., an olivine-nepheline-bearing melilitite), a vesecite (i.e., a monticellite-bearing melilitite) and a basanite. Each of these starting compositions was mixed with the fine powder of a hypothetical crustal contaminant (i.e., a marly limestone with SiO_2 = ~16 mass %, CaO = ~41 mass % and CO_2 = ~32 mass %) with incremental contamination levels of 10, 30 and 50%.

The experimental products show a variable degree of crystallization, with the runs at 1100 °C having less than 5-15% glass. Liquidus phases include olivine, melilite, clinopyroxene, nepheline, oxides, perovskite and apatite. At higher temperatures (1200 and 1300 °C), large and homogeneous glass pools were observed, with only a few samples reaching supra-liquidus conditions. Vesicles represent a common feature among the different samples.

Our preliminary results suggest that the carbonated contaminant was completely digested by the ultrabasic and mafic melts, similarly to what observed in the experiments performed at the same/similar pressure using the pure $CaCO_3$. These findings indicate that significant amounts of carbonated materials can be effectively assimilated at shallow crustal depths by ultrabasic magmas (up to a 1:1 mass ratio), producing strongly SiO_2-undersaturated, CaO-CO_2-rich melts. This has important implications for our understanding of magma-crust interaction processes and their effect on CO_2 mobilisation, which has and may be of particular relevance for the reconstruction of the deep Earth carbon cycle.

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Reconstructing the metasomatic evolution of the Kaapvaal sub-continental mantle

Innocenzi F.*[1], Day M.C.[1], La Fortezza M.[1], Agostini S.[2], Peng N.[3], Abe H.[3], Nestola F.[1], Novella D.[1], Pearson D.G.[4] & Pamato M.G.[1]

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Keywords: mantle metasomatism, stable isotopes, mantle xenoliths.

Cratons are characterised by their ancient nature (of Precambrian age, with an Archean nuclei), stability (without any tectonic activity for more than 1 Ga) and their thick lithosphere (cratonic roots deeper than 150 km; Foley, 2008; Pearson et al., 2021). All these features result in a cold cratonic lithospheric mantle capable of recording billions of years of geologic processes, while the related magmatic products (and associated mantle xenoliths and xenocrysts) provide fundamental information about mantle processes, such as metasomatism and refertilization. Although igneous activity is rare in cratonic regions, peculiar igneous lithologies such as kimberlites are often emplaced in cratonic cores, while silica undersaturated and/or alkali-rich products (e.g., ultramafic lamprophyres) crop out along continental rift systems (Foley, 2008).

This study represents a multidisciplinary characterization of a set of eleven mantle xenoliths coming from three Cretaceous kimberlite pipes - Letseng-la-Terai, Matsoku and Liqhobong – which intrude along the southeastern edge of the Kaapvaal Craton (North Lesotho, South Africa; Simon et al., 2003). These mantle xenoliths are garnet to spinel facies peridotites (lherzolite and harzburgite), which underwent metasomatic enrichment, resulting in the crystallization of phlogopite and clinopyroxene which are mostly observed in small veinlets or around garnet. Mineral chemical (major oxide compositions), spectroscopic (Fourier-transform infrared - FTIR), geochemical (trace elements) and isotopic (both stable H, B and Fe, and radiogenic Sr, Nd and Pb) analyses were conducted on each separate mineral phase to better constrain their different histories (depleted vs. refertilized). These data allowed reconstruction of the evolution of the sub-continental mantle beneath the Kaapvaal craton, where metasomatic events, related to different recycled crustal materials, variably affected the previously depleted mantle.

Acknowledgments: FI, MCD, MLFand MGP acknowledge funding from the European Union (ERC, INHERIT, Starting Grant No. 101041620).

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Helium diffusion in diamond at Earth's mantle conditions

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Keywords: helium, diffusion, diamond.

Impurities and mineral or fluid inclusions in natural diamonds can provide valuable insights into the evolution of mantle conditions through geologic time (Stachel et al., 2015). For instance, the isotopic composition of the early mantle can be inferred by studying noble gases such as helium (He) in diamonds, which may occur either as fluid inclusions or as interstitial defects in the diamond lattice. However, a critical aspect to consider is whether or not the isotopic information carried by diamonds is still representative of the original diamond-forming fluid. In fact, most diamonds experience prolonged mantle residence times at high temperature conditions, and processes such as diffusion might lead to the re-equilibration of He with the surrounding mantle, either by loss or gain of He itself. Nevertheless, several studies on He diffusion in diamond report contradictory results, both in activation energies for diffusion (which can vary over an order of magnitude) and in He diffusivity coefficients. These uncertainties are mainly due to experimental shortcomings that include graphitization of diamond, release of He after inclusion decrepitation, or the presence of cracks that act as fast diffusion pathways (Cherniak et al., 2018). As such, a further investigation of He diffusion in diamond aimed at constraining its diffusion rate at mantle conditions is essential to support the correct interpretation of He isotopic signal.

For these reasons, we investigated the diffusion of He in diamond by means of *ab initio* molecular dynamics (AIMD) and machine learning molecular dynamics (MLMD) simulations, as implemented in the Vienna Ab Initio Simulation Package (VASP). MD simulations were performed in the framework of the density functional theory (DFT) using the planar-augmented wavefunction (PAW) method and the PBE functional to estimate the exchange–correlation terms. The atoms in the simulation cell are moving according to the interatomic forces which are calculated iteratively along the MD trajectory. Machine learning techniques were used to fit interatomic potentials on the *ab initio* data, which were refined at each pressure during He diffusion along a mantle adiabat. We employed large simulation boxes (3×3×3 supercells) exploiting the *Fd3m* conventional unit cell of diamond, inside which two He atoms were randomly inserted as interstitial defects. All simulations were performed on a broad range of high pressure and high temperature conditions, compatible with those expected in the Earth's mantle where diamonds are formed. Post-processing analysis of the MD runs was carried out by means of the Universal Molecular Dynamics package (UMD, see Caracas et al., 2021 for more details). Diffusion coefficients as a function of both pressure and temperature are provided and the main petrological and geochemical implications are presented and discussed.

Acknowledgments: MLF, MCD, FI, and MGP acknowledge funding from the European Union (ERC, INHERIT, Starting Grant No. 101041620).

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Gas Resource Potential of Italy – a new national-scale Project

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Keywords: gas resources, prospect inventory map, energy security Italy.

Given the strategic importance of energy security and independence at European level, even more in the recent years of geopolitical uncertainties, a comprehensive research initiative was financed by the Italian Ministry for the Environment and Energy Security (MASE) to be carried out by a research team of the National Institute of Geophysics and Volcanology of Italy (INGV), aimed to assess National Gas Resource Potential of Italy.

This project, namely: "PROGETTO POTENZIALI MINERARI – GAS: Valutazione del potenziale risorse nazionale di gas naturale" (Gas Resource Potential Project: to evaluate the national gas potential, considering approved and non-approved reserves, as well as potential unexplored resources), aims, as primary goal, to rigorously assess Italy's domestic natural gas unexplored and undeveloped resources, focusing on the exploration potential across the country, both onshore and in the offshore.

Existing data on gas exploration potential have been retrieved at national level, with the support of the Ministry in charge of Oil&Gas resource management, and from the national-scale public ViDEPI database. Moreover, several oil and gas companies operating in Italy, such as Eni, Energean, Aleanna, Po Valley and Gas Plus, provided and shared their exploration information under confidentiality.

Gas leads and prospects have been collected and investigated all along the Italian peninsula, in different geological settings, both associated with thermogenic gas-prone basins as well as with biogenic gas plays: these included, e.g., the analysis of biogenic gas-sands in foredeep trap setting; thermogenic gas on structural traps at Apennine orogen front; Low-BTU thermogenic gas; Gas associated to oil leads and prospects; Near-field exploration; Coal bed methane (CBM).

All plays, leads and prospects natural gas resources were classified by using the PRMS as reference, in terms of Play type, Gas Initially in Place (GOIP), likely Recovery Factor, Gas Resources, their geographical location, extension and shape, depth, etc.

For a limited number of specific cases of particular interest, a dedicated G&G assessment of their exploration potential was carried out through the interpretation of subsurface data, and reserves were calculated through the use of specific 3D software.

As a result of this analysis, a national-scale Prospect Inventory Map and an associated GIS-based project were generated, in which all identified objects (leads and prospects) were reported.

In conclusion, this study provides an updated picture of Italy's natural gas potential, that could support Italy in reducing dependence on external gas import, in reaching the country's energy security goals, in improving national gas resources optimization and management, and finally in informing policymakers to plan future exploration activities.

Investigating sulfur-carbon interactions in deep mantle environments

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Keywords: deep sulfur cycle, extreme conditions, synchrotron radiation.

Sulfur (S) plays a central role in the Earth's interior, influencing a wide range of geological and geochemical processes. Thanks to its multiple valence states, it can act as a redox-sensitive element, affecting redox conditions, phase equilibria, and the mobility of volatiles in the mantle. From early differentiation (Rubie et al., 2016) to modern subduction zones (Li et al., 2020; Förster et al., 2024) sulfur has continued to shape the geochemical evolution of the deep Earth, interacting with other volatiles and phases under a wide range of pressure and temperature conditions. These interactions may regulate the speciation, mobility, and recycling of sulfur and other volatiles, such as carbon, in subduction zones and across the mantle, ultimately affecting deep geochemical cycles and mantle heterogeneity. We conducted high-pressure experiments using laser-heated diamond anvil cells to investigate interactions between iron sulfides and CO_2. We applied Synchrotron Mössbauer spectroscopy (SMS) to detect the occurrence of redox reactions through changes in Fe oxidation state, and X-ray diffraction (XRD) to identify and resolve the structure of the produced phases. SMS data showed that FeS and FeS_2 remain remarkably unreactive with CO_2 up to P = 130 GPa and T > 2000 K, with no evidence for redox reactions or changes in the Fe oxidation state. XRD patterns confirm the structural stability of the iron sulfides. Above 35 GPa, a disproportionation reaction involving FeS was observed, resulting in the formation of FeS_2 that remained stable up to the maximum pressures and temperatures reached. The observation of S-rich iron sulfide stable up to CMB conditions contrasts with previous assumptions that, with increasing depth, sulfides would become more iron-rich. Moreover, we investigated more complex Fe-S-C-O systems to find out whether reduced sulfur-rich conditions could affect the redox state or stability of relevant mantle phases. Experiments on Fe_2O_3 and $FeCO_3$ in CS_2 showed that in a binary system featuring an excess reducing S agent interacting with an oxidizing reagent, Fe-sulfides systematically form under upper mantle P-T conditions. Our results suggest that in deep mantle domains, known sulfides are the dominant sulfur species and, as such, could be more common than previously expected, with potential implications for the sequestration and deep transport of S and C. These findings raise important questions regarding the presence and persistence of S-bearing phases and the sulfur's deep cycle in the Earth's mantle which we aim to address with further experiments on more complex systems.

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Nature of the mantle-crust transition in the Finero complex (Ivrea-Verbano zone, Southern Alps)

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Keywords: Finero complex, metasomatism, alkaline magmatism.

The Finero Complex (Ivrea-Verbano Zone, Southern Alps) exposes mantle–crust sections that preserve the geochemical evolution of mantle melts extending from the Late Paleozoic to Early Mesozoic. A shift from orogenic to anorogenic-alkaline magmatism in Early Mesozoic dykes reflects a transition from post-Variscan collision to Jurassic Alpine Tethys rifting.

This study investigates the mantle-crust transition in the Rio Cannobino-Rio Creves outcrop with the aim of placing constraints on the tectono-magmatic evolution, with reference to the timing of mantle accretion to Moho levels and the sequence of magmatic pulses. Our dataset includes petrography, major and trace elements from phlogopite, amphibole, orthopyroxene, and garnet, as well as ongoing Sr-Nd-Pb isotopes of amphiboles at different levels of the mantle-crust transition.

The outcrop shows a contact from the Finero Phlogopite Peridotite (FPP) to the crustal Layered Internal Zone (LIZ). The mantle unit consists of harzburgite with phlogopite and amphibole, showing foliation parallel to the mantle/crust contact. A 1-m-thick layer of amphibole-biotite orthopyroxenite marks the mantle side of the contact, while the crustal side features layered garnet-amphibole gabbro with hornblendites.

The FPP shows chemical heterogeneity, evidencing migration of multiple LILE- depleted to enriched melts. The amphiboles in the mantle unit away from the contact is characterized by high Mg#, Ba, Rb, Cr, Sc, V contents, fractionated LREE, and low Nb, Ta and HREE. In contrast, amphiboles from the orthopyroxenite and host harzburgite are more enriched in Th, U, Fe, Al and LREE and depleted in Cr, Sc, and V.

The garnet-amphibole gabbro in the LIZ displays LREE depletion in amphibole and clinopyroxene, with a strong positive Eu anomaly also reflected in garnet. Hornblendites, composed of titanium pargasites are richer in Fe, Al, and Ti compared to the FPP and garnet-amphibole gabbro, with L-MREE-enriched convex- upward patterns and Nb and Ta enrichment.

The mineralogical and geochemical (LILE/LREE enrichment, Nb, Ta, HREE depletion) features of mantle harzburgite and orthopyroxenite at the contact, consistent with the FPP (Zanetti et al., 1999), suggest they formed during Paleozoic melt migration, facilitating FPP deformation and migration at mantle depths.

The garnet-amphibole gabbro exhibits hybrid compositions from multiple injections of LILE/LREE-depleted mantle melts that assimilated earlier plagioclase-bearing cumulates. These injections occurred after mantle emplacement at Moho depths. Later, alkaline-affinity mantle melts migrated through the hornblendites, a process recorded in the IVZ and linked to Upper Triassic– Lower Jurassic events in the Southern Alps (Ogunyele et al., 2024).

Thus, the combination of the structural and petrochemical features suggests that the FPP-LIZ transition have acted as a multistage, lithospheric discontinuity, representing a preferential zone of channeling for uprising mantle melts from the end of Variscan Orogeny to Lower Jurassic.

Ogunyele A.C. et al. (2024) - Transition from orogenic-like to anorogenic magmatism in the Southern Alps during the Early Mesozoic: Evidence from elemental and Nd-Sr-Hf-Pb isotope geochemistry of alkali-rich dykes from the Finero Phlogopite Peridotite, Ivrea–Verbano Zone. Gondwana Res., 129, 201-19, https://doi.org/10.1016/j.gr.2023.12.011.

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Tracking redox and metasomatic evolution in subduction-zone peridotites and pyroxenites: evidence from fluid and melt interactions

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Keywords: clinopyroxenite, oxygen fugacity, mantle.

Peridotites and pyroxenites preserve key signatures of the geochemical and petrological processes affecting the lithospheric mantle. In subduction zones, interactions between slab-derived fluids/melts and mantle rocks are crucial for metasomatism, redox evolution, and the deep recycling of crustal components. Yet, the redox potential of slab-derived agents remains incompletely constrained.

Garnet orthopyroxenites from the Maowu Ultramafic Complex (China) represent a case of supra-subduction mantle metasomatized by silica- and trace element-rich aqueous fluids at ~4 GPa and 750–800 °C. Solid multiphase inclusions in garnet preserve solute-rich fluids, and EELS analyses reveal significant Fe^{3+} enrichment in spinel (up to 12%), amphibole (~30%), and chlorite/phlogopite (~70%). Mass balance calculations support a redox gradient from the slab to the mantle wedge, suggesting that oxidized fluids escaping the slab-mantle interface may metasomatize the overlying lithosphere.

In the Monte Duria area (Central Alps, Italy), melt-peridotite interactions left geochemical and textural evidence in garnet peridotites. Infiltration of eclogite-derived melts formed garnet websterites and tremolitite veins, with progressive LREE enrichment over a ~120 m profile. This gradient reflects reactive melt flow modifying the trace element inventory of the mantle. Numerical modelling supports eclogitic melts as the source of the observed signatures.

Additional constraints come from graphite–sulfide–magnetite-bearing garnet clinopyroxenites of the External Ligurian ophiolites (Northern Apennines, Italy), crystallized from eclogite-derived melts at ≥3 GPa and 1100 °C. Fe^{3+}/Fe^{2+} partitioning in garnet and clinopyroxene reveals a redox evolution from oxidized conditions (ΔFMQ = -1.25 to 0) to highly reduced states (ΔFMQ < -5) during decompression. This trend implies graphite precipitation via reduction of an initially oxidized carbon-bearing phase, in a closed system with negligible late-stage fluid/melt interaction. These redox trajectories affect the behavior and retention of deep carbon and sulfur.

Together, these case studies illustrate how peridotites and pyroxenites track the complex interplay between melt-peridotite interaction, metasomatism, and redox processes near the slab-mantle interface. Integration of micro- to nanoscale redox data with whole-rock geochemistry offers valuable insights into the chemical evolution of subduction-modified mantle domains.

New insights on sulfur recycling in the mantle from high-precision isotope analysis of pyroxenite-hosted sulfides

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Keywords: mantle, pyroxenite, sulfur isotope.

Crust-derived pyroxenites are considered a key component of mantle heterogeneity. However, to date, no S isotopic data are available in literature for recycled pyroxenite-hosted sulfides. Here we present S isotope analyses for garnet clinopyroxenites from the External Ligurian (EL) mantle sequences in the N Apennines, along with selected samples from the orogenic massifs of Ronda and Beni Bousera (Betic-Rif Belt). This study aims to integrate these data into established pyroxenite petrogenetic models, to advance our understanding of S geochemical cycling. In situ measurements of $\delta^{34}S$ have been carried out by SIMS on primary Fe-Ni-Cu sulfides (BMS). Previous geochemical and isotopic studies indicate that the EL pyroxenites originated from MORB-like gabbroic precursors with a long residence time in the mantle (> 1 Ga; Montanini et al., 2012). The Ronda and Beni Bousera massifs exhibit a variety of pyroxenite types, including corundum-bearing garnet clinopyroxenites and UHP garnet clinopyroxenites with graphitized diamond pseudomorphs. These lithologies display wide Sr-Nd-Hf-Pb-O isotopic variability reflecting origin from oceanic crust affected by seafloor alteration, mixing with pelagic sediments and, possibly, involvement of continental lower crust (Pearson et al., 1993; Lorand et al., 2021, Varas Reus et al., 2018). The S isotope signature of the EL garnet clinopyroxenites overlaps depleted mantle values ($\delta^{34}S$ = -2.84 to +0.83 ‰ relative to VCDT), in agreement with the lack of an oxygen isotope signature distinctive of hydrothermal alteration (Montanini et al., 2012). In contrast, $\delta^{34}S$ measured for Ronda and Beni Bousera (ranging from 6.03 to +4.80‰) deviate significantly from depleted mantle values, reflecting diverse processes and sulfur sources, such as the preservation of isotopic signatures from hydrothermally altered oceanic crust, desulfidation of sedimentary pyrite under reducing conditions, or input from recycled continental lower crust.

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Mantle complexity beneath the Oslo Rift: geochemical insights into the earliest phase of the Skagerrak-Centered LIP

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Keywords: Oslo rift, alkali basalts, mantle source.

The Oslo Rift marks the northernmost extent of the Skagerrak-Centered Large Igneous Province (SCLIP; Torsvik et al., 2008), where mafic volcanism first erupted around 300 Ma with the emplacement of the so-called "B1" basalts. These lavas, deposited rapidly over ~1–2 million years, now form stacks up to 1500 meters thick and offer a unique glimpse into early rift evolution and mantle dynamics at the onset of SCLIP activity.

We present a rift-scale geochemical portrait for the B1 lavas from five lava piles – from south to North: Brunlanes, Skien, Vestfold, Jeløya, Krokskogen. The lavas show a striking latitudinal gradient – from highly alkaline melilitites in the south (Brunlanes) to tholeiites in the north (Krokskogen), despite their roughly coeval emplacement in these different areas (Corfu et al., 2024). This chemical transition includes systematic variations in trace elements and radiogenic isotopes, pointing to the involvement of at least four distinct mantle sources.

The southernmost, strongly alkaline lavas from Brunlanes derive from a plume-like, mildly carbonated, mantle component with low initial Sr-Nd isotope ratios (LoNd type; Hyung et al., 2023). We favor a deep-seated (kimberlite-like) plume origin for this component, but we also consider the possibility of metasomatized lithospheric domains enriched by melts or fluids shortly before the onset of magmatism.

A second source exhibits HIMU-like Sr-Nd-Pb isotope signatures and high incompatible element concentrations. A third, enriched mantle (EM-type) source contributes a less incompatible-element-rich component.

The Skien B1 series reflects melting of a hybrid mantle involving all three components, while Vestfold and Jeløya basalts record mixing between HIMU-like and EM-type sources. We propose that the lower lithosphere beneath the Skien-Vestfold-Jeløya region was originally EM-type garnet peridotite, later metasomatized by HIMU-like melts that formed enriched veins long before SCLIP initiation. These B1 melts likely formed at ≥140 km depth, during or immediately before lithospheric thinning.

A fourth, depleted mantle source that escaped metasomatic enrichment, was only tapped by the Krokskogen tholeiitic basalts in the north, and likely formed at shallower depths, suggesting rapid thermal erosion of the lithosphere in the north.

Understanding the multi-source evolution of the B1 basalts is critical for reconstructing the earliest magmatic stages of the SCLIP and assessing their potential role, via CO_2 degassing, in Carboniferous–Permian climate perturbations (Wang et al., 2023).

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Kimberley diamonds record mantle uplift and changing geothermal regimes since the Archean: insights from inclusion–host elastic modelling

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Keywords: diamond, inclusion-host systems, thermobarometry.

De Beers Pool diamonds (Kimberley, South Africa) are characterized by anomalous proportions of composite inclusions consisting of both touching and non-touching mineral grains. Thermobarometry of these inclusions has puzzled scientists for many years. Most non-touching orthopyroxene–garnet inclusions record higher temperatures than touching inclusions, but both types record conditions colder than mantle xenoliths from the same pressure range. These contrasting P–T estimates have generated discordant interpretations, such as secular cooling of the lithosphere after diamond formation (Phillips et al., 2004), recent diamond formation from cold, slab-derived fluids (Weiss et al., 2018), and diamond formation under various thermal regimes (Nimis et al., 2020). However, none of these scenarios fully accounts for the observed thermobarometric data.

We propose an alternative scenario based on elastic theory of inclusion–host systems, which reconciles the contrasting P–T estimates (Nimis et al., 2025). Forward model calculations show that P–T conditions similar to those estimated for the touching inclusions can result from the development of overpressures on the inclusions, consequent to diamond decompression ± heating. Thus, in our scenario, 'reequilibrated' touching inclusions in Kimberley diamonds are not colder than 'pristine' non-touching inclusions and fully equilibrated xenoliths from the same depths. Rather, the touching inclusions record higher *pressures* than non-touching inclusions and xenoliths from the same depths and temperatures. Our model requires initial diamond formation under transient conditions colder than a 35-mW/m² geotherm, followed by mantle uplift (~ 60 km, possibly multi-stage) and reequilibration on the Late Cretaceous xenolith geotherm (~ 40 mW/m²). The initial cold conditions could be promoted by foundering of shallow lithospheric materials due to subduction or other Archean-style foundering processes. Cooling of the mantle would cause development of garnet exsolutions from mantle orthopyroxenes and thus increase the probability for the early-forming diamonds to incorporate touching orthopyroxene–garnet inclusions. The subsequent large uplift may be the result of Archean and possibly, in part, later tectonic events. Cratonic amalgamation at 2.9–2.7 Ga and earlier Archean-style compressional tectonics, lithospheric inversion or harzburgite diapirism are good candidates. These events may have been associated with or may have followed a change in the lithospheric thermal regime, which has been recorded by different generations of diamonds. The diamonds with the 'warmer' non-touching inclusions belong to one or more generations of uncertain age, which formed after substantial textural reworking of the mantle on a relaxed geotherm that was still distinctly colder (~ 37 mW/m²) than the Late Cretaceous xenolith geotherm.

Nimis P. et al. (2020) - Diamond's depth distribution systematics. Lithos, 376-377, 105729, https://doi.org/10.1016/j.lithos.2020.105729.

Nimis P. et al. (2025) - Multistage diamond formation, mantle uplift and changing geothermal regimes recorded by inclusions in Kimberley diamonds. Mineral. Petrol., https://doi.org/10.1007/s00710-025-00908-2.

Phillips D. et al. (2004) - Mineral chemistry and thermobarometry of inclusions from De Beers Pool diamonds, Kimberley, South Africa. Lithos, 77, 155-179, https://doi.org/10.1016/j.lithos.2004.04.005.

Weiss Y. et al. (2018) - Inclusions in diamonds constrain thermo-chemical conditions during Mesozoic metasomatism of the Kaapvaal cratonic mantle. Earth Planet. Sci. Letters, 491, 134-147, https://doi.org/10.1016/j.epsl.2018.03.014.

Ca-rich environments in the deep mantle revealed by inclusions in super-deep diamonds

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Keywords: sublithospheric diamond, carbonitite, merwinite.

Earth's deepest naturally occurring materials are super-deep diamonds (SDDs), which crystalize within the mantle at depths of 300 to 800 km. These rare diamonds, found in kimberlites from a wide range of cratons, offer a unique window into the processes of the deep mantle and their relationship with the supercontinental cycle. Our study focused on two SDD samples: AZ2, recovered from the Juína region of Brazil, and KK33, found in Kankan, Guinea. Both SDD samples date to the Neoproterozoic-Paleozoic (450–650 Ma) and were sourced from alluvial deposits.

In both diamonds, in-situ single-crystal X-ray diffraction measurements identified inclusions of periclase, merwinite, and diopside. Significantly, the occurrence of merwinite + diopside in KK33 marks the first such report outside of Juína. The Mg-rich periclase composition of AZ2 supports a lower mantle source, a characteristic likely shared by KK33. Furthermore, FTIR spectroscopy indicates that AZ2 is Type IIa (nitrogen-free), while KK33 is Type IaB (low-nitrogen, highly aggregated). This high degree of nitrogen aggregation in KK33 suggests a minimum mantle residence temperature of approximately 1400 °C, a finding consistent with thermodynamic modeling.

By combining these observations with CaO-MgO-SiO_2 system modeling, we propose that the observed mineral assemblage formed at transition zone pressures and at temperatures exceeding 1400 °C. Our results indicate that the presence of this mineral assemblage points to significant metasomatic processes involving subduction-related Ca-rich melts and the surrounding mantle at considerable depths.

Iron isotopic composition of the lithospheric mantle: Insights from a magnesiochromite inclusion in diamond

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Keywords: diamond, magnesiochromite, Fe isotopes.

Iron isotope compositions of natural specimens are routinely exploited in geosciences to investigate environmental and planetary processes. For example, the concentration of Fe isotopes of mantle materials has been used to explore and understand mantle composition and differentiation, since it depends on processes such as partial melting or the presence of chemically distinct lithologies. As such, a precise knowledge of the Fe isotopic composition of mantle minerals and rocks, and the processes controlling Fe isotopes fractionation, is needed to understand the formation, evolution and heterogeneity of the mantle.

The lithospheric mantle is directly sampled by extreme volcanic eruptions such as kimberlites, which bring to the surface minerals (xenocrysts) or rocks (xenoliths) from as deep as 300 km. Many studies have investigated the Fe isotopic composition of these specimens from different localities worldwide in the past, highlighting a large variation that is a complex reflection of processes including partial melting and rock-fluid alteration and/or different redox conditions. Diamonds are also found in kimberlitic rocks and are capable of sampling deep (> 300 km) portions of the mantle by including minerals and protecting them on their way up to the surface, preventing secondary alteration processes. Therefore, diamonds are precious alternative to xenoliths to investigate the deep, inaccessible and non-altered mantle. However, diamonds are very rare, and their mineral inclusions are commonly very small (100-200 um across) making the investigation of Fe isotopic composition of mineral inclusions in diamonds extremely challenging.

In this study, we determined, for the first time, the Fe isotopic composition of a single magnesiochromite inclusion found in a lithospheric diamond from Panda kimberlite (Ekati Mine, Canada). Magnesiochromite is a common inclusion in lithospheric diamonds, which in some instances can be Fe rich (14 wt% FeO) and relatively large (up to 1 mm across), allowing precise Fe isotopic analyses to be preformed by multicollector inductively coupled plasma mass spectrometry. The new results will be discussed to provide new insights into the systematics of Fe isotopes in the deep Earth and the geochemical composition and evolution of the lithospheric mantle.

Recent post-collisional alkaline magmatism in NW Iran (East and West Azerbaijan)

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Keywords: alkaline magmatism, post-collisional, Iran.

Continental collision zones are characterized by igneous activity showing very variable changes in whole-rock chemistry, mineral paragenesis and volcanological facies. It often shows a close association of rocks with contrasting geochemical features, with "subduction-related" and "intraplate-like" characteristics, albeit hybrid compositions are not so rare. Such diverse fingerprints suggest multiple petrogenetic processes operating at both regional and local levels.

North-western Iran stands out as a crucial area for understanding these events. Its geological record preserves many key tectonomagmatic events that shaped the Cenozoic evolution of Iran and the Lesser Caucasus. The Cenozoic magmatic activity in NW Iran largely reflects magma derivation from subduction-modified mantle sources, occurring during active subduction or, more commonly, in post-collisional tectonic settings. By the late Cenozoic, the chemical spectrum of erupted rocks expanded to include Miocene potassic to ultrapotassic compositions, joined by products with adakitic affinities and overall calcalkaline geochemical and mineralogical features.

During the latest phases, a diffuse, albeit volumetrically minor, Pliocene-Quaternary activity took place mostly in NW Iran, also with moderately to strongly ultrabasic compositions. The overall geochemical compositions of the youngest products resemble intraplate-like magmatic but showing evidence of derivation from subduction-modified mantle regions.

The East and West Azerbaijan districts in NW Iran are part of the extensive ~1800-km long NW-SE trending Cenozoic Urumieh-Dokhtar Magmatic Arc. A petrographic, mineral chemical, geochemical and isotopic study on the recent volcanic products exposed within a roughly 40,000 km² area around the Urumieh Lake, between Jolfa and Buchan, reveals diverse mineral assemblages including melilite-, foids- and feldspar-bearing rocks with olivine and clinopyroxene as the most common mafic minerals, and minor phlogopite. The 27 investigated rocks exhibit a wide spectrum of compositions from ultrabasic to intermediate (SiO_2 = 41.7-58.5 mass %, MgO = 12.7-2.5 mass %) up to rare acid types (SiO_2 up to 67.5 mass %) with sodic to potassic alkaline character (Na_2O = 2.3-4.7 mass %; K_2O = 0.3-5.6 mass %). Primitive mantle-normalized multielemental patterns display variable enrichments in Rb, Ba, Th and U alongside depletions in Nb, Ta and Ti; they also exhibit highly variable Pb concentrations and significant Rare Earth Element (REE) fractionation, providing evidence of a subduction-modified mantle. Sr-Nd-Pb isotopic compositions confirm the derivation from mantle sources with a complex geological heritage, reflecting variable processes including partial melting extraction, melt-fluid refertilization and occasional processes of crustal contamination of melts en-route to the surface.

Melilitites and nephelinites: experimental constraints on their mantle source

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Keywords: magma genesis, carbonate.

Olivine melilitites and nephelinites are ultramafic magmas predominantly found in within-plate settings. In the Alaotra Lake volcanic district (Madagascar), olivine melilitites exhibit high Mg# values (68–77), suggesting compositions close to mantle-derived melts. Similar to many global occurrences, including plutonic equivalents, these low-silica magmas (with olivine and monticellite, spinel, melilite, clinopyroxene, perovskite, nepheline, apatite, Ba-phlogopite) lack primary amphibole, with F-rich phlogopite as the main hydrous phase. This indicates a limited role of H_2O during differentiation.

Experimental studies have reproduced melilititic melts at ~3 GPa under high melt fractions in the CaO-MgO-Al_2O_3-SiO_2-CO_2 system, and through reactions between carbonated MORB-eclogite partial melts and fertile peridotite. At lower pressures (~1.5 GPa), melting of amphibole-bearing metasomatized lithosphere has been proposed as an alternative mechanism. Liquidus phase relations of carbonated melilitites indicate stability of clinopyroxene alongside olivine or garnet.

Based on previous experimental work on alkaline melts, we investigate the melting behavior of clinopyroxene-rich carbonated peridotites at 3.2 GPa, above the "solidus ledge". Peridotite compositions with variable silica and clinopyroxene/garnet ratios were prepared as mechanical mixtures of San Carlos olivine, diopside, aegirine, dolomite, and kyanite. Samples were loaded in graphite capsules within sealed platinum capsules, with vitreous carbon spheres and synthetic diamond grains used as liquid traps.

Preliminary experiments (3.2 GPa, 950-1450 °C) indicate a solidus temperature around 1100 °C for a model wehrlite composition. In runs relatively silica-rich, an orthopyroxene-rich layer with polygonal microstructure formed at the interface between olivine, clinoyroxene, garnet and quenched liquids. At 1150-1200 °C such liquids are are melilititic, with ~2.5 to 4 wt.% TiO_2 on a volatile-free basis.

A second set of sandwich experiments explores the equilibration of olivine melilitite and nephelinite from Ankaratra (Madagascar) with peridotite compositions. At 3.2 GPa and 1150 °C, a larnite-normative liquid, compositionally intermediate between melilitite and nephelinite, was generated, in equilibrium with olivine, clinopyroxene, and garnet.

These preliminary results suggest that the generation of low-silica magmas is controlled by the garnet/clinopyroxene ratio within the forsterite-enstatite-nepheline-larnite volume in the presence of CO_2.

A novel fast-quench system for a Walker-type multi-anvil apparatus

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Keywords: experimental petrology.

We present a newly developed fast-quench system designed for a Walker-type multi-anvil apparatus. This system is optimized for large-volume samples and integrates a series of engineering modifications to significantly enhance quenching efficiency. Key design features include modified wedge dimensions, newly designed tapered tungsten carbide WC cubic anvils, and two 3D-printed thermoplastic polyurethane (TPU) sheaths, which collectively improve thermal control and cooling performance.

The system employs two independent cooling mechanisms to regulate different structural components: (1) steel temperature control via common ergal plates and (2) high-pressure assembly outer temperature control through a -10 °C glycol chiller circuit, which cools the WC anvils via the TPU sheaths. To accommodate large-volume samples, the system utilizes cubes with a 32 mm edge length and a 17 mm truncation edge length (TEL), coupled with octahedral pressure media of 25 mm edge length. This configuration is well-suited for experiments requiring precise control over phase transitions, glass preservation, and volatile retention.

Real-time monitoring of temperature distribution and quench rates is achieved using a National Instruments thermocouple module and a data acquisition (DAQ) system, which records temperature fluctuations at a temporal resolution of 10 milliseconds across four independent thermocouples. This high-speed data collection allows for detailed analysis of quench dynamics, enabling fine-tuning of experimental conditions.

Preliminary results indicate that our system achieves significantly higher cooling rates compared to conventional multi-anvil quenching methods, offering new opportunities for the study of metastable phase assemblages, preservation of volatile speciation, and element partitioning under high temperature conditions.

Origin of H_2O-rich mantle magmas emplaced in the deepest levels of the Ivrea-Verbano Zone

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Keywords: amphibole, accretion of continental crust, Sr-O isotopic micro-analyses.

The archetypal lower crustal section of the Ivrea-Verbano Zone (Italian Alps) includes the Mafic Complex, an 8 km-thick gabbronorite-diorite body built during the post-Variscan transtensional tectonics. At its deepest levels, the Mafic Complex encloses several amphibole-rich mafic-ultramafic bodies indicating a crystallization from H_2O-rich melts. The present contribution wishes to define the compositional characteristics of the parental magmas and to achieve information about the nature of their mantle sources. For this purpose, we combined trace element, Sr and O isotopic micro-analyses of amphibole from amphibole-bearing dunites and pyroxenites, hornblendites and amphibole-rich gabbros, which were collected from four mafic-ultramafic bodies exposed within the Mafic Complex and from an adjacent mafic-ultramafic lens known as Monte Capio sill. Overall, amphibole has pargasite to titanian pargasite compositions and 67-88 Mg#; in the gabbroic rocks, it is associated with plagioclase having 75-91 mol% anorthite. Amphibole from the selected rock samples displays wide variations in incompatible trace element signature and initial $^{87}Sr/^{86}Sr$, which nevertheless remains highly radiogenic. On the other hand, the $\delta^{18}O$ amphibole fingerprint is nearly homogeneous and comparable to that of typical mantle amphibole. We relate these geochemical characteristics to H_2O-rich mantle magmas that were primarily compositionally heterogeneous. It is speculated that the mantle source of these magmas was variably metasomatized and enriched in H_2O by the Variscan subduction event.

The nature of the mantle exhumed to the Thyrrenian sea: results of IODP Expedition 402

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Keywords: mantle peridotites, oceanic mantle, continent-ocean transition

Two mantle sections have been drilled by Expedition 402 of the International Ocean Discovery Program (IODP) in the Tyrrhenian Sea (Zitellini et al., 2025). Contrary to the mantle drilled at Mid Ocean Ridges and hyperextended passive margins, the mantle from this embryonic ocean is exceptionally heterogeneous, and chemically fertile (Sanfilippo et al., 2025). Rock-types range from lherzolites to depleted harzburgites and dunites, interlayered with pyroxenite layers. Most of the mantle lithologies suffered some degree of interaction with melts, as shown by plagioclase- and clinopyroxene-rich layers. Mineral chemistry also agrees with equilibration with melts, which caused selective increases in incompatible elements in otherwise depleted lithologies. The re-fertilization process was followed by the injection of hydrous potassic magmatic veins, containing magmatic phlogopite, with zircon and rutile as accessory phases. Meter-scale mafic intrusions, ranging from olivine-gabbros to norites and diorites, are the only evidence for a plutonic crust, associated with the synchronous crystallization of granitoids. Our preliminary data indicate that the formation of a proper oceanic crust in the Tyrrhenian Sea was delayed by deep lithospheric processes. Hence, large areas of refertilized mantle were likely exhumed to the seafloor soon after the continental breakup, before the formation of a steady state spreading center.

Zitellini N. et al. (2025) - Proceedings of the International Ocean Discovery Program, Volume 402. publications.iodp.org, https://doi.org/10.14379/iodp.proc.402.101.2025.

Sanfilippo A. et al. (2025) - Heterogeneous Earth's mantle drilled at an embryonic ocean. Nature Commun., https://doi.org/10.1038/s41467-025-57121-0.

Geochemical variations of the lower oceanic crust from the ultra-slow spreading Gakkel Ridge (Arctic Ocean)

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Keywords: lower oceanic crust, trace elements, radiogenic isotopes.

Gakkel Ridge is the slowest spreading ridge on Earth with a full rate of 14.6-6 mm.yr^{-1}. It is located in the Artic and extends over ~1,800 km. Bathymetric and gravity data show variations in crustal thickness and architecture, which reveal three tectono-magmatic provinces: i) Western Volcanic Zone (WVZ), ii) Sparsely Magmatic Zone (SMZ), and iii) Eastern Volcanic Zone (EVZ) (Michael et al., 2003). Basalts and mantle peridotites from these provinces have been extensively studied in literature, whereas the chemical composition of the gabbros is poorly known. Here we present texture, geochemistry and isotope compositions of gabbros collected in different locations from these three provinces. The SMZ gabbros range from troctolites to oxide gabbros and felsic veins, while the WVZ and EVZ gabbros are characterized by a lack of the most evolved and primitive lithologies, respectively. Despite the overall geochemistry of the Gakkel gabbros agrees with that of other ultra-slow spreading ridges, mineralogy and mineral chemistry differentiate the gabbros from WVZ from those in SMZ, and EVZ, which seem more enriched in volatiles and highly incompatible elements. In detail, the SMZ and EVZ gabbros contain abundant magmatic amphibole and have plagioclase with lower anorthite (An) and FeO but higher K_2O than in WVZ, while clinopyroxene has higher Na_2O. In accordance, the Cpx Mg# vs Plg An covariation diagram shows that the SMZ and EVZ gabbros are displayed at lower Plg An values compared to WVZ. The incompatible trace element compositions of clinopyroxene and plagioclase from SMZ reveals high LREE/M-REE ratios relative to both, WVZ and EVZ. Sr-Nd-Hf-Pb isotopes in gabbros, in addition, show difference in the mantle sources of the three provinces, with variations in radiogenic isotopes extending the field of Gakkel MORB. In this contribution we discuss the compositional variation of the Gakkel gabbros, showing the potential of lower oceanic crust to reveal mantle source heterogeneity.

Michael P.J. et al (2003) - Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean. Nature, 423, https://doi.org/10.1038/nature01704.

Unveiling sulfur behaviour in deep Earth fluids: a novel protocol for measuring sulfur volatiles in experimental high-pressure and high-temperature fluids

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Keywords: sulfur, subduction zones, experimental petrology.

Subduction zones are key sites of chemical exchange between Earth's surface and interior. In these settings, slab dehydration promotes elemental transfers from the subducting plate into the overlying mantle wedge, triggering hydrous melting and magma generation. The input of oxidized components via slab-derived fluids is widely invoked to explain the elevated oxidation state of arc magmas relative to those formed in other geological settings, such as mid-ocean ridges. However, the specific nature of these oxidizing agents and the mechanisms governing the transfer of redox-sensitive elements remain poorly understood.

Among these, sulfur stands out as a critical yet elusive component in the regulation of mantle redox conditions, largely due to its poorly constrained behavior under high-pressure, high-temperature (HP–HT) conditions. This knowledge gap arises from the lack of experimental data and the significant analytical challenges associated with detecting and quantifying sulfur-bearing volatiles, particularly given the extremely low fluid volumes in experimental capsules and the high chemical reactivity of sulfur species. Consequently, our capacity to model volatile transport and assess its impact on mantle redox evolution is still limited.

In this contribution, we present a novel experimental and analytical protocol for accurately quantifying sulfur-bearing volatiles (H_2S, SO_2) in HP–HT fluids. A series of experiments was conducted under geologically relevant subarc conditions (P = 3 GPa, T = 700 °C) with controlled redox conditions and run durations ranging from six hours to one week. The resulting volatile species were analyzed using the unique capsule-piercing device coupled with a quadrupole mass spectrometer available at the University of Milan (Tiraboschi et al., 2016).

Our results confirm that the bulk fluid composition is preserved during synthesis, quenching, and fluid analysis, validating thermodynamic predictions. Notably, we demonstrate that chemical equilibrium between the solid and fluid phases is achieved rapidly – within five hours – and that sulfide phases remain stable and inert even under moderately oxidizing conditions.

This novel methodology represents a major advancement in the experimental study of sulfur volatiles in subduction-related fluids, providing a robust framework for investigating sulfur behavior in deep Earth environments, modelling volatile cycling and ore-forming processes in convergent margins.

Tiraboschi C. et al. (2016) - Quantitative analysis of COH fluids synthesized at HP–HT conditions: an optimized methodology to measure volatiles in experimental capsules. Geofluids, 16, 841-855, https://doi.org/10.1111/gfl.12191.

Dynamic topography and the mantle forcing on climate: a missing link in Earth system science

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Keywords: dynamic topography, climate, mantle flow.

Global topography plays a fundamental role in shaping climate, influencing atmospheric circulation and precipitation patterns through orographic effects. While much of Earth's topography arises from isostatic support due to variations in crustal and lithospheric thickness and density, a significant portion of up to ± 1-2 km results from dynamic forces driven by slow yet vigorous mantle convection. Despite decades of research on the spatial and temporal evolution of such 'dynamic topography', its impact on global climate remains unexplored. In this study, we address this gap by quantifying the influence of mantle-induced dynamic topography on present-day atmospheric circulation and precipitation patterns. Using an Earth Model of Intermediate Complexity forced with different models of global dynamic topography, we isolate the mantle's contribution to climate patterns. Our findings reveal prominent climatic effects linked to mantle dynamics, particularly along the American Cordillera, the East African Rift System, and other regions across latitudes which are critical to biodiversity and the evolution of life. These results uncover a hitherto unknown connection between Earth's deep interior and surface environments, with the mantle dynamics as active driver of climate processes, enhancing our understanding of the Earth System. By linking mantle dynamics to global climate, our study offers new opportunities for paleoclimate investigations and insights into how geodiversity and biodiversity have co-evolved throughout Earth's history.

On the origin of the Eoarchean dunites from the Narssaq ultramafic complex (southern West Greenland)

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Keywords: Eoarchean, mantle, dunite.

The Archean mantle is an invaluable source of information about the geodynamic processes active during the early Earth. The Eoarchean Narssaq ultramafic complex within the Itsaq Gneiss Complex of southern West Greenland is one of the most extensively studied Eoarchean ultramafic sections. According to van de Locht et al. (2020), the ultramafic complex represents a remnant of the Archean mantle. Conversely, Zhang & Zilas (2024) proposed a cumulate origin for the same lithologies. Such contrasting interpretations have significant implications for the inferred geodynamic scenario active during the Eoarchean.

We carried out a new field survey on the Narssaq ultramafic complex collecting representative samples of dunites, hornblende peridotites and associated metagabbros and orthogneisses. Here we focus on dunites which are the most primitive lithologies. Olivine (Fo_{90-91}) is the dominant rock forming mineral of dunites; spinel (variably transformed in magnetite and Fe-chromite), phlogopite and amphibole are accessories. Mineral phases were characterized for major and trace elements concentration by electron microprobe and laser ablation ICP-MS, respectively. On selected amphiboles, images on trace element distribution were also carried out by LA-ICP-TOF-MS.

Olivine is characterised by exceptionally low contents of incompatible trace elements and high contents of Ni and fluid mobile elements (B and Li). Amphibole is mostly tremolitic in composition but locally preserves core ghost domains consisting of Mg-hornblende. The latter is characterized by high Cr and Ni contents and flat to slightly LREE enriched chondrite-normalized REE pattern at about 10 times CI chondrite with a marked negative Eu anomaly. Mg-hornblende also shows relatively high concentrations of crustal (e.g., Pb, Th, U) and fluid mobile elements (e.g., Li, Be and B).

The transition metal trace element signature of olivine could be reconciled with a mantle origin of the dunites; however, relict amphiboles clearly point to a crustal origin. The Narssaq dunites are thus interpreted as the product of a melt rock reaction process between an original ultramafic assemblage of mantle origin and a K-rich melt with a high crustal component. The B content in olivine resembles values typically found in olivine from the mantle wedge. However, these high B concentrations are accompanied by exceptionally high Li contents - more than three times those observed in olivine from the mantle wedge. The origin of the high B-Li in olivine is still unclear.

van De Locht J. et al. (2020) - Preservation of Eoarchean mantle processes in 3.8 Ga peridotite enclaves in the Itsaq Gneiss Complex, southern West Greenland. Geochim. Cosmochim. Acta, 280, 1-25.

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Molecular hydrogen incorporation in SiO_2 polymorphs at subduction conditions: implications for redox processes in the Earth's interior

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Keywords: deep hydrogen cycle, SiO_2 polymorphs, high-pressure experiments.

Hydrogen affects a wide range of petrological, geochemical and geodynamic processes within the Earth's interior, ultimately contributing to sustain plate tectonics. Traditionally, H_2O and hydroxyl groups (OH^-) have been regarded as the primary hydrogen carriers at depth. However, recent evidence of molecular hydrogen (H_2) trapped within the structure of eclogitic and mantle minerals highlights the potential importance of H_2 in the deep hydrogen cycle.

To investigate the mechanisms of H_2 incorporation in silicates, we performed piston-cylinder and multianvil experiments (1–9.6 GPa, 500–950 °C, $\Delta FMQ \approx -5.7$ to +0.4) using a model system composed of crystalline SiO_2 and water. Fluids coexisting with SiO_2 were analyzed via a capsule-piercing device connected to a quadrupole mass spectrometer. In most experiments, the quenched fluids contained significantly higher H_2 concentrations than those measured in SiO_2-free reference runs or predicted by thermodynamic models of H–O fluids buffered at the same redox conditions. This excess H_2 is attributed to its incorporation into quartz and coesite at high pressure and temperature, followed by rapid release during quench and depressurization.

We interpret this phenomenon as a form of "zeolitic" adsorption (physisorption) within sub-nanometric structural cavities in quartz and coesite. Adsorbed H_2 concentrations range from ~100 to ~2100 μg/g SiO_2, increasing with pressure and under reducing conditions, but decreasing with temperature. Consistent with the "zeolitic" adsorption hypothesis, the transition to stishovite, which has a denser rutile-like structure, leads to a dramatic decrease in the incorporated H_2.

Our findings indicate that H_2 incorporation into crystalline SiO_2 could reach a maximum in the forearc-to-subarc regions of subduction zones. The nearly complete reversibility of the adsorption process implies that variations in pressure, temperature, or redox conditions –such as those caused by slab sinking, faulting, melt infiltration, or the input of oxidizing fluids– can trigger substantial H_2 release. Molecular hydrogen desorption potentially serves as an alternative source of H_2 alongside serpentinization reactions and could locally alter the redox state of the surrounding rocks and fluids, also promoting the reduction of redox sensitive elements, such as carbon. In environments where H_2 fugacity becomes sufficiently high, highly mobile and reactive H_2-rich fluids may be generated and their potential migration to the mantle wedge may drive hydrous redox melting.

New insights into the origin of amphibole-bearing dunites from the Meso-archaean Seqi Ultramafic Complex, SW Greenland

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Keywords: accretion of Archean crust, ultramafic cumulates, peridotite metasomatism.

Several amphibole-bearing peridotite bodies interpreted as magmatic cumulates occur in the orthogneisses of the Akia Terrane, North Atlantic Craton of SW Greenland (e.g., Szilas et al., 2015). Despite the numerous investigations, there are still uncertainties about the origin of the magmas forming these ultramafic cumulates and about the nature of the included amphibole. Here we consider the well-known case study of the ~3.0 Ga Seqi Ultramafic Complex, which covers a total area of ~0.5 km^2 and mostly consists of amphibole- and orthopyroxene-bearing dunites (Szilas et al., 2018; Wang et al., 2024). Previous studies emphasized the refractory nature of the Seqi dunites, as for instance shown by the forsterite-rich olivine (mostly 91-93 mol%), and reported a wide compositional range for the coexisting spinel (e.g., Cr# = 26-97), which was partly related to the post-emplacement metamorphic evolution. It was also highlighted that the bulk rock incompatible trace element signature of the Seqi dunites display similarities with Phanerozoic boninites, although a potential genetic relation of the trace element compositions with a crustal contamination process was not excluded. The amphibole (Mg-hornblende) in the Seqi dunites was generically interpreted of metamorphic origin.

We have carried out new major and trace element analyses of minerals from the Seqi amphibole-bearing dunites. Within a single rock sample, we have found that spinel enclosed by olivine has a relatively narrow compositional range compared to spinel interstitial to olivine, which is typically associated with chlorite and, locally, with Cr-magnetite, tremolite, magnesite, dolomite and/or serpentine. Olivine and spinel inclusion pairs provide a direct correlation between the forsterite component of olivine and the Cr# of spinel, thereby confirming the cumulus origin for the Seqi Ultramafic Complex. Notably, the low Cr# (24-41) of olivine-hosted spinel argues against an origin from boninite-type magmas.

Mg-hornblende in the Seqi dunites has variable contents of Al_2O_3 (4-9 wt%) and Na_2O (0.5-1.8 wt%), and low TiO_2 (0.3-0.8 wt%). It displays chondrite-normalized REE patterns characterized by pronounced negative Eu anomaly, enrichment of HREE over MREE, and flat to slightly enriched LREE. The highest REE amounts (up to 90 times chondrite) were observed for the Mg-hornblende having the highest Al_2O_3, Na_2O and TiO_2, which is also distinct in the high concentrations of K, Ba, Rb, Th, Pb and Li. Overall, the compositional characteristics of the Mg-hornblendes are difficult to reconcile with the magma forming the olivine + spinel cumulates. Mg-hornblende in the Seqi dunites was most likely generated by pervasive percolation of an externally derived agent, a H_2O-rich melt possessing a substantial crustal component and/or a high-temperature H_2O-rich fluid. The melt-fluid infiltrating event resulted in a metasomatic modification of the original bulk rock signature of incompatible trace elements.

Szilas et al. (2015) - Peridotite enclaves hosted by Mesoarchaean TTG-suite orthogneisses in the Fiskefjord region of southern West Greenland. GeoResJ, 7, 22-34, http://dx.doi.org/10.1016/j.grj.2015.03.003.

Szilas et al. (2018) - Highly refractory Archaean peridotite cumulates: Petrology and geochemistry of the Seqi Ultramafic Complex, SW Greenland. Geosci. Frontiers, 9, 689-714, http://dx.doi.org/10.1016/j.gsf.2017.05.003.

Wang et al. (2024) - Age and petrogenesis of Archaean chromitite from the Seqi Ultramafic Complex, southern West Greenland. Lithos, 482-483, 107714, https://doi.org/10.1016/j.lithos.2024.107714.

Carbon isotopic heterogeneities from subducted sediments: Implications for CO_2 transfer to arc magma sources

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Keywords: graphite, high pressure, slab.

The isotopic composition of CO_2 emitted by arc volcanoes provides critical insight into the recycling of crustal components and the development of chemical heterogeneities in sub-arc mantle sources. These emissions are strongly influenced by the nature and composition of subducted sediments, which represent a major carbon reservoir. In particular, redox reactions involving organic matter (graphite) and carbonate minerals during subduction control the amount and isotopic signature of CO_2 released into the mantle wedge. In a previous study (Tumiati et al., 2022), we proposed a model in which the $\delta^{13}C$ of arc CO_2 is controlled by the isotopic buffering of graphite-derived CO_2 by coexisting carbonate, and primarily governed by the resulting $CO_2/CaCO_3$ ratio. This formulation assumed that the presence of both graphite and carbonate was sufficient to fix the fluid composition, in agreement with classical thermodynamic predictions. However, this approach did not fully account for natural scenarios where the graphite/carbonate ratio becomes extreme. In such cases, particularly near compositional endpoints, the system may deviate from ideal buffering behavior and exhibit a more gradual isotopic transition. To test this, we conducted new high-pressure, high-temperature experiments simulating a range of sedimentary carbon mixtures with controlled proportions of cultivated coccolithophores and green algae, representative of inorganic and organic carbon sources, respectively. In parallel, we used thermodynamic modeling based on the Deep Earth Water (DEW) model, incorporating variable reaction rates. Our combined approach shows that, although carbonate remains an effective isotopic buffer, the resulting $\delta^{13}C$ of CO_2 varies in a non-linear way at both low and high graphite/carbonate ratios. This behavior reflects a progressive isotopic exchange rather than a sharp buffering threshold, indicating that phase proportions — especially near compositional endpoints — influence the isotopic outcome more than previously assumed. To better predict these behaviors, we developed a new mathematical correction model that refines and extends our earlier formulation. This correction improves predictions of carbon speciation in graphite-saturated systems (GCOH fluids) and supports a direct comparison between experimental data and thermodynamic simulations. The consistency observed between the two approaches confirms that reaction progress and phase proportions play a critical role in controlling the mobility and isotopic composition of carbon-bearing fluids under subduction zone conditions. These results provide new constraints on the transfer of isotopically distinct carbon from subducted sediments to the mantle source of arc magmas. Ultimately, this work contributes to a more accurate picture of volatile recycling and the generation of geochemical heterogeneities in the upper mantle, with implications for arc volcanism and the global carbon cycle.

Tumiati S. et al. (2022) - Subducted organic matter buffered by marine carbonate rules the carbon isotopic signature of arc emissions. Nature Commun., 13, 2909, https://doi.org/10.1038/s41467-022-30421-5.

Tracing the Phanerozoic evolution of the subcontinental mantle of the Adriatic plate: partial melting, lithospheric accretion, metasomatism

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Keywords: SCLM, mantle metasomatism, lithospheric accretion.

The Ivrea-Verbano Zone (IVZ), in the western Southern Alps, is an exhumed key cross-section of the lower continental crust of the Adriatic Plate, down to the mantle transition. Exhumation followed the Variscan orogenic cycle, culminating in Alpine continental collision. Large orogenic mantle peridotites are mostly aligned along the Insubric Line, with some of them still rooted in the Adriatic subcontinental lithosphere. They represent in-situ mantle sections in primary contact with lower crustal sequences. Major orogenic mantle massifs include Balmuccia, Baldissero, Premosello and Finero. The first three, in the southern-central IVZ, are predominantly residual lherzolites, which underwent low degrees of partial melting (3-5%) closely followed by subordinated pervasive-to-focused episodes of melt migrations during their lithospheric accretion, constrained by Nd-Hf isochrons at ca. 370 Ma, presumably in a continental back-arc setting (Ogunyele et al., 2024).

The Finero Phlogopite Peridotite, in northeastern IVZ (FPP), is the largest of these mantle massifs and underwent extensive melt extraction (ca. 20%) at 450 Ma or before. The sequence was pervasively metasomatized during Upper Carboniferous-Lower Permian (310-290 Ma; Voshage et al., 1987; Zanetti et al., 2016; Malitch et al., 2017). Such Paleozoic porous flow melt migration events were concomitant to pervasive deformation and produced segregation of phlogopite, amphibole and secondary orthopyroxene, with formation of phlogopite- and amphibole-bearing harzburgites and pyroxenites (mostly websterites and orthopyroxenites). Successively, large concordant replacive dunite channels developed parallel to the harzburgite's foliation planes, hosting chromitites and phlogopite-bearing pyroxenites and hornblendites (Zanetti et al., 2016; Malitch et al., 2017). The last migration events in the Paleozoic formed meter-scale discordant dunite channels and phlogopite-bearing orthopyroxenite/hornblendite veins (cm-wide) cross-cutting all the previous rocks. New determinations of isotopic Nd–Hf–Sr–Pb–O composition of the FPP reveal a strong affinity with Variscan post-collisional lamprophyres involving large volumes of continental crust components. If recycled into the deeper mantle, such metasomatized domains may evolve into enriched reservoirs, sampled by hotspots and ocean floor basalts.

Malitch K.N. et al. (2017) - Laurite and zircon from the Finero chromitites (Italy): New insights into evolution of the subcontinental mantle. Ore Geol. Rev., 90, 210-225, https://doi.org/10.1016/j.oregeorev.2017.06.027.

Ogunyele A.C. et al. (2024) - Accretion of "young" Phanerozoic subcontinental lithospheric mantle triggered by back-arc extension: The case of the Ivrea-Verbano lherzolites. Sci. Rep., 14, 11805, https://doi.org/10.1038/s41598-024-61763-3.

Voshage H. et al., (1987) A Nd and Sr isotopic study of the Ivrea zone, Southern Alps, N-Italy. Contrib. Mineral. Petrol., 97, 31-42, https://doi.org/10.1007/BF00375212.

Zanetti A. et al., (2016) - Origin and age of zircon-bearing chromitite layers from the Finero phlogopite peridotite (Ivrea–Verbano Zone, Western Alps) and geodynamic consequences. Lithos, 262, 58-74, https://doi.org/10.1016/j.lithos.2016.06.015.

S2.

Advances in mineral sciences: exploring Earth and rocky bodies' building blocks

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Guastoniite-(Y): a new pegmatitic mineral from Tajikistan

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Keywords: guastoniite-(Y), pegmatite, new minerals.

Guastoniite-(Y) is a new mineral with ideal formula $Pb_4(YCa)(Si_8B_4O_{28})F$ (triclinic, space group *I*-1) recently approved by the CNMNC (IMA No. 2024-082). It was found at the Moraine of Darai-Pioz glacier, Tien-Shan, Rashtskiy district, Republic of Tajikistan. The new mineral honours Dr. Alessandro Guastoni (1966-2022) for his significant contribution to the world of mineralogy with a special focus on the mineralogy, petrology and geochemistry of pegmatites. Dr. Guastoni was the curator of the Museum of Mineralogy of University of Padova, Italy (the present Museum of Nature and Humankind which has now the Section of Mineralogy dedicated to Guastoni who organized the present mineral collection). Dr. Guastoni left us in December 2022, and we think he really deserves to be honoured with a new mineral that reflects the mineralogy that he loved his entire life.

Guastoniite-(Y) (symbol: Gsn-Y), the 69th new mineral discovered in Tajikistan, is associated with microcline, aegirine, polylithionite, quartz, tadzhikite-(Y), leucosphenite, dusmatovite, reedmergnerite, hyalotekite, cesium-kupletskite, tienshanite, maleevite, calcybeborsilite-(Y) and datolite. Guastoniite-(Y) occurs in a specific polylithionite-aegirine-quartz-microcline pegmatite. The mineral was formed during a late-stage, probably hydrothermal phase of pegmatite evolution. Its hardness is about 5.3 (Mohs scale) and the measured density is 3.83 g/cm^3. Guastoniite-(Y) is biaxial positive. The Raman spectrum of guastoniite-(Y) is characterized by several peaks, the most intense at 1105, 1028, 958 cm^{-1} (Si-O and B-O stretches) and at 713, 658, 606 cm^{-1} (Si-O-Si bridges). The empirical formula of guastoniite-(Y) is:

$$(Pb_{1.90}Ba_{1.65}K_{0.40}Na_{0.05})[(Y_{1.05}Ln_{0.17})(Ca_{0.49}Mn_{0.24}Na_{0.06})](Si_{8.08}B_{3.94}Be_{0.02}Al_{0.02}O_{28.01})F_{0.99}$$

where $Ln_{0.17} = Er_{0.05}Yb_{0.04}Dy_{0.03}Gd_{0.02}Ho_{0.01}Tm_{0.01}Lu_{0.01}$ and Y^{3+} is the dominant *REE*.

Guastoniite-(Y) is a new member of the hyalotekite group (memorandum 57-SM/16, Hawthorne et al. 2018) and is isostructural with hyalotekite, $Ba_4Ca_2[Si_8B_2(SiB)O_{28}]F$, kapitsaite-(Y), $Ba_4(YCa)(Si_8B_4O_{28})F$, and khvorovite, $Pb^{2+}{}_4Ca_2[Si_8B_2(SiB)O_{28}]F$. Its main structural unit is an interrupted framework of corner-sharing SiO_4 and BO_4 tetrahedra.

Hawthorne F.C. et al. (2018) - Chemographic exploration of the hyalotekite structure-type. Mineral. Mag., 82, 929-937.

Crystal chemistry of tinzenite and relations with axinite group minerals

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Keywords: axinite, tinzenite, crystal chemistry.

Fifteen samples of Mn-rich axinite have been studied to determine the compositional relations and intracrystalline cation distribution along the axinite-(Mn)-tinzenite series. Results obtained demonstrate that the studied samples contain from 5 to 83 % of tinzenite endmember, the latter being among the highest values known in literature. Some samples have homogeneous composition close to either axinite-(Mn) or tinzenite endmembers, but the others have intermediate composition, thus indicating that the series is complete. Moreover, the samples with intermediate composition very often show a large chemical zoning, with a typical trend from an axinite-(Mn)-rich core to a tinzenite-rich rim, in agreement with the core-rim Mn enrichment observed for axinite in the literature.

In accord with axinite crystal chemistry (Andreozzi et al., 2000, 2004), for all samples the X1 site is predominantly or totally occupied by Ca. However, the X2 site may be occupied by Ca or Mn^{2+} in largely variable proportions, and it is definitely the dominance of Ca or Mn^{2+} that justifies the assignment of the names axinite-(Mn) or tinzenite, respectively (Basso et al., 1973; Grew, 2018). The Y site is always dominated by Mn^{2+}, but in all the studied samples minor amounts of Mn^{3+} are required by stoichiometry. The calculated amount of Mn^{3+} increases proceeding from axinite-(Mn) to tinzenite, being 8 % of Mntot, and it is supposed to partially substitute for Al at the Z sites (namely Z1), similarly to what observed for Fe^{3+} in axinite-(Fe,Mn) samples.

Linear relations between chemical composition of the samples and their unit-cell parameters are observed. From axinite-(Mg) to axinite-(Fe) to axinite-(Mn), all cell parameters *a, b, c* and *V* linearly increase as a function of increase of Fe and Mn incorporation at the Y site. However, the same parameters strongly decrease towards tinzenite, that is for Mn_{tot} contents exceeding 2 apfu, due to incorporation of Mn^{2+} at the X2 site substituting for the larger Ca.

Andreozzi G.B. et al. (2000) - Crystal chemistry of the axinite-group minerals: a multianalytical approach. Am. Mineral., 85, 698-706.

Andreozzi G.B. et al. (2004) - Site distribution of Fe^{2+} and Fe^{3+} in the axinite mineral group: New crystal-chemical formula. Am. Mineral., 89, 1763-1771.

Basso R. et al. (1973) - La struttura della tinzenite. Per. Mineral., 42, 369-379.

Grew E. (2018) - Tinzenite, a member of the axinite group with formula revised to $Ca_2Mn^{2+}_4Al_4[B_2Si_8O_{30}](OH)_2$. Eur. J. Mineral., 30, 177-182.

Pure and Sc-doped diopside ($CaMgSi_2O_6$) vibrational spectra: modelling and experiments

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Keywords: doped-diopside, IR and Raman spectroscopy, *ab-initio* calculation.

The incorporation of trace elements in minerals is crucial in geosciences and material sciences, as doping can alter physical properties and affect partition coefficients that describe uptake or release of elements, depending on their solubility and structural accommodation (local structure environment and coupled substitutions to achieve charge neutrality). In pyroxenes, this principle has been used to estimate crystallisation pressures and cooling rates in magmatic systems (Nazzareni et al., 2020, 2021). Diopside ($CaMgSi_2O_6$), with its relatively simple yet sensitive structure, can host small amounts of transition metals like Li, Sc, Ti, Ga, Fe, depending on parameters like pressure, temperature, and oxygen fugacity. Scandium, sharing chemical similarities with rare earth elements and substituting Mg in octahedral coordination, was used to dope a series of diopside crystals. Their average crystal structure obtained by single-crystal X-ray diffraction (SC-XRD) describes the coupled substitution of Sc^{3+} at M1 octahedron suggesting a charge balance by vacancy at M2 site (Nazzareni et al., 2013). We compared the structure obtained from *ab-initio* modelling techniques at the density functional theory (DFT) level with the structure solved by employing SC-XRD. Furthermore, we compared IR and Raman spectroscopy experiments with vibrational density of states (VDOS) calculated from the Fourier transform of the velocity autocorrelation function obtained processing *ab-initio* (DFT) molecular dynamics simulations. In this framework, we developed a computational tool to assign the vibrational mode associated with a specific frequency (Bellucci et al., 2024). The comparison of the two models suggests that when the diopside structure is doped with Sc the main effects are the broadening of the peaks above 1000 cm^{-1} together with a shoulder at ca. 860 cm^{-1}, and the occurrence of a small peak at 700 cm^{-1}, which could be ascribed to the presence of vacancy at M2. The best model also suggests that the vacancies are in proximity to the nearby Sc site, in agreement with a distribution of bond valences associated with the trivalent cations substituting the divalent Mg. We speculate that the position of this peak could be related to the average distance between the Sc and the vacancies; however, this topic represents the main object of further investigations. Overall, the computed VDOSs are in good agreement with the measured Raman and IR spectra, and provide a more detailed interpretation of the spectroscopic signature of the samples. In particular, we could correlate the M1 polyhedral distortion due to the Sc-doping to the broadening of the low frequencies Raman peaks. We are confident that the application of this method can offer a comprehensive characterisation of complex systems, such as minerals or nanomaterials.

Bellucci L. et al. (2024) - Pure and Sc-doped diopside (CaMgSi2O6) vibrational spectra: modelling and experiments. Phys. Chem. Chem. Phys, 26, 4029, https://dx.doi.org/10.1039/D3CP02324A.

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New crystal chemical data on morimotoite, $Ca_3(Ti^{4+}Fe^{2+})(SiO_4)_3$

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Keywords: morimotoite, garnet supergroup, titanium.

Among garnet-supergroup minerals, four are characterized by Ti as essential chemical constituent, i.e., schorlomite, $Ca_3Ti_2(Fe^{3+}{}_2Si)O_{12}$, hutcheonite, $Ca_3Ti_2(Al_2Si)O_{12}$, both belonging to the schorlomite group, rubinite, $Ca_3Ti^{3+}{}_2(SiO_4)_3$, and morimotoite, $Ca_3(Ti^{4+}Fe^{2+})(SiO_4)_3$, belonging to the garnet group. The actual status of this latter mineral has been questioned by some authors owing to the similar chemical composition and unit-cell parameters with schorlomite (e.g., Rass, 1997; Antao, 2014). A recent finding of two new Italian occurrences of morimotoite allowed the collection of new crystal chemical data, confirming its status as a valid mineral species.

The first occurrence was from the Varenna Valley (Genoa Province, Liguria), where morimotoite was found as compositional domains within Ti-bearing andradite in a metarodingite dyke hosted in serpentinites belonging to the Palmaro-Caffarella Unit (Voltri Group). Electron microprobe indicated the chemical formula $^{X}(Ca_{3.05}Mn^{2+}{}_{0.01})_{\Sigma=3.06}{}^{Y}[(Ti_{0.62}Fe^{2+}{}_{0.62})Al_{0.55}Fe^{3+}{}_{0.17}]_{\Sigma=1.96}{}^{Z}(Si_{2.62}\square_{0.38})O_{10.48}(OH)_{1.52}$ for the Ti-richest composition. The occurrence of (OH) groups is confirmed by micro-Raman and FTIR spectroscopy. Single-crystal X-ray diffraction study gave the unit-cell parameters a = 12.074(4) Å, V = 1760.0(19) Å^3, space group *Ia*-3*d*. The crystal structure was refined to R_1 = 0.0484 for 150 unique reflections with $F_o > 4\sigma(F_o)$ and 20 least-square parameters.

In 2022 a new occurrence of morimotoite was discovered in the ophiolitic complex of Monte Ferrato (Prato Province, Tuscany), where this garnet forms euhedral {110} crystals, compositionally homogeneous, hosted in a rodingite dyke hosted in serpentinites of the Monte Morello Unit. Electron microprobe data gave the formula $^{X}(Ca_{2.97}Fe^{2+}{}_{0.02}Mn^{2+}{}_{0.01})_{\Sigma=3.00}{}^{Y}[(Ti_{0.75}Zr_{0.01}Fe^{2+}{}_{0.55}Mg_{0.21})Al_{0.26}Fe^{3+}{}_{0.21}V_{0.02}]_{\Sigma=2.01}{}^{Z}(Si_{2.69}\square_{0.31})O_{10.78}(OH)_{1.17}F_{0.05}$. Also in this case the occurrence of (OH) groups is supported by micro-Raman spectra. Single-crystal X-ray diffraction study gave the unit-cell parameters a = 12.1069(4) Å, V = 1774.59(18) Å^3, space group *Ia*-3*d*. The crystal structure was refined to R_1 = 0.0274 for 301 unique reflections with $F_o > 4\sigma(F_o)$ and 20 least-square parameters.

The crystal structure refinements of both samples confirmed the occurrence of Ti at the *Y* site and the presence of vacancies at the *Z* site, in accordance with electron microprobe data. A relationship between the occurrence of Ti^{4+} and the presence of (OH) groups was observed, in agreement with some previous authors (e.g., Armbruster et al., 1998).

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Dominant valency/charge rule vs. chemical endmember approach: a thermodynamic perspective on mineral identification

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Keywords: IMA-CNMNC, dominant-valency rule, Gibbs free energy of mixing.

According to the IMA-CNMNC, mineral species should be identified by an endmember formula. In principle, two main approaches can be used for determining this formula: the dominant-charge arrangement and the dominant-chemical arrangement (Hatert & Bruke, 2008; Bosi et al., 2019). These two approaches have significant thermodynamic implications, highlighting key differences in how mineral species are identified and how their stability is assessed. The dominant-valency rule, endorsed by IMA–CNMNC, and its extension, the site-total-charge (STC) method, prioritizes charge of ions by identifying the prevailing valency state at specific crystallographic sites. In contrast, the endmember approach relies on the prevalence of specific chemical constituents.

In ternary feldspars ($NaAlSi_3O_8$–$CaAl_2Si_2O_8$–$KAlSi_3O_8$), compositions assigned using the dominant endmember charge arrangement (e.g., albite in Na/Ca/K-rich systems) display lower differences in the Gibbs free energy of mixing compared to those assigned directly via the chemical endmember approach (e.g., anorthite). For example, the composition $(Ca_{0.40}Na_{0.35}K_{0.25})(Al_{1.40}Si_{2.60})O_8$ is attributed to albite, due to dominance of monovalent ions, even though Ca is the most represented cation. Thermodynamic calculations performed with different solution models available from the literature for ternary alkali feldspars (e.g., Ghiorso, 1984; Fuhrman & Lindsley, 1988) confirm that this composition is energetically closer to albite-rich configurations, underscoring the predictive power of the charge-based framework in identifying stable mineral assemblages.

Although some critics argue that the charge-based approach can lead to counterintuitive classifications, such as attributing the composition $(Ca^{2+}_{0.40}Sc^{3+}_{0.35}Y^{3+}_{0.25})(S^{6-}_{0.4}P^{5-}_{0.6})O_4$ to a phosphate endmember charge arrangement $[3^+(PO_4)]_{0.6}$ despite the prevalence of the chemical endmember $(CaSO_4)_{0.4}$, such examples illuminate the core tension between valency-based and constituent-based schemes. Nonetheless, thermodynamic coherence consistently supports the STC method. This ongoing debate underscores a fundamental divide: charge-based rules (STC) versus constituent dominance (chemical endmember approach), with thermodynamic evidence favoring the former as a more robust and internally consistent basis for mineralogical nomenclature.

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A first structural model for nakauriite

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Keywords: nakauriite, crystal structure, carbonate.

Nakauriite was described by Suzuki et al. (1976) as a copper sulfate-carbonate-hydroxide-hydrate mineral from the Nakauri mine, Shinshiro city, Aichi Prefecture, Japan. However, later findings did not confirm the occurrence of (SO_4) groups in this species (e.g., Braithwaite & Pritchard, 1982; Palenzona & Martinelli, 2007).

The examination of a specimen of nakauriite from Monte Ramazzo (Genoa Province, Liguria, Italy) allowed the collection of single-crystal X-ray diffraction and chemical data (EDS mode). Nakauriite is monoclinic, space group *P*2/*m* (#10), with $a = 7.898(5)$, $b = 3.1037(15)$, $c = 9.626(5)$ Å, $\beta = 111.947(17)°$, $V = 218.9(2)$ Å^3. The crystal structure was solved through direct methods. Nakauriite is affected by non-merohedral twinning and the crystal structure was refined using the *HKLF*5 method (e.g., Bolte, 2004). The final model refined to $R1 = 0.0741$ for 1594 reflections with $F > 4\sigma F$ (0.1095 for all 2487 unique reflections) and 52 refined parameters.

The crystal structure of nakauriite is characterized by three independent cation sites and four anion sites, forming corrugated {100} layers. The three cation sites, namely Mg(1), Mg(2), and Mg(3), have site occupancy ($Mg_{0.639(14)}Cu_{0.361(14)}$), $Mg_{1.00}$, and ($Mg_{0.588(14)}Cu_{0.412(14)}$), respectively. The four O sites, O(1)-O(4), are occupied by (OH) groups, the only exception being the O(3) site that may have a mixed [$(OH)_{0.5}(H_2O)_{0.5}$] occupancy. Considering site multiplicity, the chemical formula of {100} layers of nakauriite is $[(Mg_{3.23}Cu_{0.77})(OH)_7(H_2O)]^{1-}$ ($Z = 1$). Partially occupied interlayer sites are occupied by C and O atoms, the latter belonging to both CO_3 and H_2O groups. The composition of the interlayer is $\{(CO_3)_{0.5}\cdot H_2O\}^{1+}$ ($Z = 1$). The partially occupied nature of interlayer sites and some short and mutually exclusive distances suggest the occurrence of an undetected superstructure with $b' = 2b$. The chemical formula of nakauriite should be written as $[(Mg_{3.23}Cu_{0.77})(OH)_7(H_2O)](CO_3)_{0.5}\cdot H_2O$ ($Z = 1$). It is possible that in the ordered structure, Mg and Cu^{2+} occupy distinct sites, supporting the ideal formula $Mg_3Cu(OH)_7(H_2O)(CO_3)_{0.5}\cdot H_2O$.

This composition agrees with the results of the chemical analysis, that gave (in wt%) MgO 38.20, CuO 23.95, Fe2O3 0.61, total 62.76. On the basis of (Mg + Cu + Fe) = 4 atoms per formula unit, the chemical composition of the {100} layers correspond to ($Mg_{3.02}Cu_{0.96}Fe^{3+}_{0.02}$). Thus, nakauriite is a hydrated magnesium-copper hydroxide-carbonate and not a hydrated copper sulfate-carbonate-hydroxide compound. A formal proposal for its redefinition will be submitted to the IMA-CNMNC.

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Marioantofilliite, $[Cu_4Al_2(OH)_{12}](CO_3)\cdot 3H_2O$, a new LDH mineral from Liguria (Italy)

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Keywords: new mineral, Layered Double Hydroxides, crystal structure.

Marioantofilliite, ideally $[Cu_4Al_2(OH)_{12}](CO_3)\cdot 3H_2O$, is a new mineral species discovered in the Monte Copello – Reppia Cu prospect, Graveglia Valley, Genoa Province, Liguria, Italy. It occurs as globular aggregates, up to 1 mm in diameter, sometimes covered with μm-sized prismatic crystals, associated with allophane and malachite in vugs of "limonite".

Preliminary X-ray powder diffraction data revealed that this mineral is the natural analogue of synthetic (Cu-Al) Layered Double Hydroxide (LDH) phases described by several authors (e.g., Yamaoka et al., 1989; Britto and Kamath, 2009). Such a relationship with LDH phases is further supported by micro-Raman spectroscopy. This latter technique, along with thermo-gravimetric (TG) and evolved-gas analyses, supports the occurrence of CO_2 and H_2O in the studied material. Electron microprobe data, coupled with the results of TG analysis, give the empirical formula $[Cu^{2+}_{4.23}Mg_{0.02}Al_{1.76}(OH)_{12}](CO_3)_{0.82}(SO_4)_{0.01}[Si(OH)_6]_{0.05}\cdot 3H_2O$, ideally $[Cu_4Al_2(OH)_{12}](CO_3)\cdot 3H_2O$. Unit-cell parameters, refined using single-crystal X-ray diffraction data, are a = 5.590(3), b = 2.9358(11), c = 7.675(3) Å, β = 100.958(17)°, V = 123.66(9) Å^3, space group $C2/m$. The crystal structure was solved and refined to $R1$ = 0.0372 for 181 reflections with $F > 4\sigma F$ and 23 least-square parameters.

The crystal structure of marioantofilliite is topologically similar to that of other members of the hydrotalcite supergroup (Mills et al., 2012). It shows a distorted {001} brucite-like layer, with Cu and Al statistically occupying an octahedrally-coordinated site. In the interlayer, disordered CO_3 and H_2O groups were located. The existence of an ordered superstructure is very probable, even if superstructure reflections have not been observed yet, mainly due to the very small size of the available crystals (e.g., the size of the crystal used for structure refinement is 0.035 × 0.006 × 0.006 μm).

Marioantofilliite honours Mario Antofilli (1920–1983) for his contribution to the knowledge of the mineralogy of Liguria. Both the mineral and its name have been approved by the IMA-CNMNC under the number IMA 2025-012.

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Crystal structure of truscottite

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Keywords: truscottite, crystal structure, gyrolite-group.

The layered silicate truscottite has been originally described (Hövig, 1914) in a sample from the Lebong Donok Mine, Sumatra, Indonesia, and in the past century several other occurrences have been reported from Japan (Toi mine, Shizuoka prefecture; Hishikani deposit, Kagoshima Prefecture), Israel (Hatrurim Formation) and United States (Yellowstone National Park and in deep drill hole at Kilauea Volcano). It is a Calcium Silicate Hydrate (C-S-H) phase belonging to the gyrolite group (e.g., Bonaccorsi & Merlino, 2005). Its crystal structure was related to that of reyerite by Gard et al. (1975) and Lachowski et al. (1979); the latter authors suggested the chemical composition $Ca_{14}(Si_{24}O_{58})(OH)_8 \cdot xH_2O$, where $x \sim 2$. However, despite its interest as a C-S-H mineral and its structural relationships with gyrolite and reyerite, no structural data were available until now, mainly because of the poor quality of natural samples.

The examination of a specimen of truscottite from the type locality (Lebong Donok Mine, Rejang Lebong District, Bengkulu Province, Indonesia) allowed the extraction of a thin plate that was suitable for the collection of single-crystal X-ray diffraction data. Truscottite is trigonal, space group *P-3* (# 147), with $a = 9.709(4)$, $c = 18.845(11)$ Å, $V = 1538.5(15)$ Å^3. The crystal structure was solved through direct methods and refined to $R_1 = 0.1549$ for 1425 reflections with $F_o > 4\sigma F$ (0.2018 for all 2101 unique reflections) and 162 refined parameters.

The crystal structure of truscottite is characterized by nine independent cation sites, namely Ca(1)-Ca(3) and Si(1)-Si(6), and fourteen anion sites. The latter sites can host O^{2-} anions, $(OH)^-$ groups, and free interstitial H_2O groups. The crystal structure of truscottite is layered, with the alternation, along **c**, of three different kinds of {0001} structural units:

- a layer of silicate tetrahedra of composition $[Si_8O_{20}]^{8-}$ (layer S_1);
- a layer of Ca-centered polyhedral with composition $[Ca_7(OH)_4]^{10+}$ (layer O);
- a double layer of silicate tetrahedra with interstitial H_2O groups and composition $[Si_{16}O_{38}]^{12-} \cdot 3H_2O$ [layer S_2–(-S_2)]

The crystal structure can be described as the sequence S_1–O–S_2–(-S_2)–(-O) and the resulting chemical composition is $Ca_{14}(OH)_8[Si_{24}O_{58}] \cdot 3H_2O$ ($Z = 1$).

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Ferro-bosiite from the Marina pegmatite, Mozambique: composition, crystallography, and genesis

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Keywords: new mineral species, tourmaline, granitic pegmatites.

Ferro-bosiite, a rare Fe^{2+}–Fe^{3+} member of the tourmaline supergroup, was identified in the Marina granitic pegmatite, Mozambique. The ideal formula is $NaFe^{3+}_3(Fe^{2+}_2Al_4)(Si_6O_{18})(BO_3)_3(OH)_3O$ (Bosi et al., 2022).

In the Marina pegmatite, ferro-bosiite occurs as black, acicular crystals forming late-stage overgrowths on the analogous poles of pre-existing, multi-colored fluor-elbaite. Its crystallization was triggered by a structural collapse of a pegmatitic pocket, which exposed amphibolitic wall rock to circulating hydrothermal fluids. This event led to a sudden release of Fe and Mg, likely derived from the alteration of amphibolite, creating a chemical environment favourable for the crystallization of Fe-rich tourmalines. Depending on the local fluid composition and crystallographic growth sectors, ferro-bosiite developed in some zones, while dravitic and schorlitic overgrowths formed in others. These growth patterns produced prominent sector zoning, including typical "hourglass" structures, which reflect abrupt changes in fluid composition and crystallographic control during rapid crystal growth.

Tourmalines associated with ferro-bosiite show a continuous compositional trend that ranges from Mg-rich, relatively Fe^{3+}-poor varieties to Fe^{3+}-dominant members approaching the dutrowite compositional field. This evolution follows the sequence: oxy-dravite → oxy-schorl → ferro-bosiite → dutrowite, with minor contributions from the bosiite component. The classification of these tourmalines depends strongly on the Fe^{3+}/Fetot ratio and the Ti content, as both influence the incorporation of O^{2-}, replacing OH and F. Similar Ti-rich tourmalines have been described in other pegmatitic environments, such as Řečice (Czech Republic; Flégr et al., 2017), Juliana (SW Poland; Pieczka & Sęk, 2017), and Land's End granite (SW England; Drivenes, 2022), but those specimens generally contain insufficient Fe^{3+} to qualify as ferro-bosiite and are best classified as schorl.

Ferro-bosiite from Marina was characterized using single-crystal X-ray diffraction, electron microprobe analysis, Mössbauer spectroscopy, infrared spectroscopy, optical absorption spectroscopy, and micro-LIBS. Ferro-bosiite has trigonal symmetry (space group *R*3*m*), with unit cell parameters a = 16.0499(5) Å, c = 7.2977(2) Å, V = 1628.03(11) Å³, and Z = 3. The empirical formula, based on structural, chemical, and spectroscopic data, is:

$$(Na_{0.99}K_{0.02})\,(Fe^{3+}_{1.56}V^{3+}_{0.02}Mg_{1.01}Fe^{2+}_{0.20}Mn^{2+}_{0.03}Ti_{0.16}Li_{0.02})\,(Al_{4.32}Fe^{3+}_{0.41}Fe^{2+}_{1.22}Mg_{0.05})$$
$$[(Si_{5.99}Al_{0.01})O_{18}]\,(BO_3)_3\,(OH)_3\,[O_{0.62}(OH)_{0.34}F_{0.04}]$$

The occurrence of ferro-bosiite in the Marina pegmatite illustrates the capacity of late-stage hydrothermal processes to produce compositionally complex tourmalines through interaction with host rock lithologies. Its study offers valuable insights into the interplay between crystal chemistry, fluid-rock interaction, and crystallization dynamics in pegmatitic environment.

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Alluaudite-type arsenates from Valletta mine (Canosio, Cuneo, Italy)

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Keywords: alluaudite-type arsenates, Valletta mine, crystal structure.

Valletta mine is the remains of an old mining operation, probably an open pit, located at the head of the Valletta Valley (2560 m a.s.l.), near Canosio, in the Maira Valley (Cuneo, Piedmont). Up to 61 valid minerals have been observed in the remaining mining dumps, which consist of dispersed dark quartzites with quartz veins that contain a large variety of mineral phases rich in arsenic, vanadium, barium, and strontium (Baratelli, 2021; Conforti, 2024). Valletta mine is the type locality of 8 species, all As-bearing, mostly arsenates, with 4 of them belonging to the group of arsenbrackebuschite. Alluaudite-type arsenates (AtA) have been also reported, but no systematic work has been undertaken so far. There are 22 AtA species that have the formula A(2)A(1)M(1)M(2)$_2$(AsO$_4$)$_3$, with monoclinic *C*2/*c* space group (Hatert, 2019). Seven out of the 22 species also have H as defining component in AsO$_3$OH or AsO$_2$(OH)$_2$ groups, or as H$_2$O in the *A*(1) and *A*(2) channel sites.

Here we report the results of the study on alluaudite-type arsenates from Valletta, which have been analysed using single crystal X-ray diffraction, electron microprobe (WDS mode) and Raman spectroscopy. Samples have been provided by R. Bracco, G. Odicino and G.C. Piccoli. In Valletta there are alluaudites of type 2 ((Na$_2$M$^{2+}_2$Fe^{3+}(PO$_4$)$_3$), Hatert, 2019) and therefore are characterised by a chemical formula similar to that of badalovite, Na$_2$Mn$^{2+}_2$Fe^{3+}(AsO$_4$)$_3$ (Pekov et al., 2020), presenting a progressive and identical exchange of Mg for Mn^{2+}, almost in the absence of Fe^2, related to substitutions in the *M*(1) and *M*(2) sites. Some crystals also show the exchange of Fe^{3+} by Mn^{3+}, in agreement with other Mn^{3+} dominant species present in Valletta as lombardoite (Ba$_2$Mn^{3+}(AsO$_4$)$_2$(OH)) or aldomarinoite (Sr$_2$Mn^{3+}(AsO$_4$)$_2$(OH)). In several samples, Mn^{3+} exceeds Fe^{3+} at the *M*(2) sites, indicating new potential mineral species. A limited Na$_{-1}$Ca substitution at the *A*(1) sites occurs, but Ca never becomes dominant and therefore no arseniopleite (NaCaMnMn$_2$(AsO$_4$)$_3$, Hatert, 2019) compositions are observed. Raman spectra reveal that the OH stretching and H$_2$O bending signals are absent, indicating that these compositions have no H. The most intense Raman shift, which is observed at ca. 840 cm^{-1} (corresponding to the (AsO$_4$)$^{3-}$ stretching) is correlated with the composition of the *M*(2) site: compositions with Mn^{2+}Mn^{3+} show values close to 840 cm^{-1}, while those with Mg^{2+}Fe^{3+} show values close to 855 cm^{-1}, and a linear correlation is observed among Raman shift and observed site scattering at *M*(2) sites. A similar trend is observed for the Raman shift at ca. 415 cm^{-1} ((AsO$_4$)$^{3-}$ bending), but it is less evident and clearly shows dependences on other factors.

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Relationships between boron coordination in LCT pegmatite fluids and boron isotope record of tourmalines

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Keywords: tourmaline, boron isotope, LCT pegmatites.

Lithium-cesium-tantalum (LCT), peraluminous pegmatites provide more than half the global production of lithium necessary for the ongoing energy transition, most of the tantalum and all of the cesium. Demand for these metals will increase many times in few decades and a better understanding of petrological processes leading to the formation of LCT pegmatites is needed. The geochemical and isotopic signature of LCT pegmatites suggest a derivation from magmas that formed by partial melting of predominantly marine sediments and metasedimentary rocks. However, their extremely variable mineralogy and texture generated several classification schemes and genetic models that are still highly debated in the scientific community. This contribution addresses the formation of LCT pegmatites (Tuscany, Pakistan, Russia and Madagascar) belonging to the "Complex Type" (elbaite sub-type) of the miarolitic class, providing isotopic data (B, O, H, Sr) and trace element data on zoned tourmalines and associated feldspars, quartz and micas. Isotopic data (B, O, Sr) measured on tourmaline from granites, early- to late-pegmatitic zones and hydrothermal veins, are consistent with crustal-derived magmatic systems. Oxygen isotope geothermometer ($\delta^{18}O_{tur\text{-}qtz}$) provides temperatures that are consistent with a progressive temperature decrease from 700 to 350 °C. Pegmatitic, zoned (schorl-elbaite), tourmalines recorded small variation in boron isotope composition that are not consistent with what would be expected from the calculated and experimental fractionation factors. Therefore, it is possible that trigonal boron was not present in the fluid/melt as simple $B(OH)_3/BO_3$, but rather as polymerized building units, which were directly incorporated in tourmaline with negligible isotopic fractionation. Boron in peraluminous, hydrous rhyolitic melt is dominantly trigonal, but the complex structure of aluminous-silicate melts favors the formation of complex combinations with network-forming components of $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$. Similarly, $[BO_3]^{3-}$ in tourmaline form networks with $[SiO_4]^{4-}$ and $[AlO_6]^{9-}$. Only in the final stage tourmaline from hydrothermal veins and overgrowths recorded boron isotopic compositions consistent with available fractionation factors and with the stability of $B(OH)_3$ in aqueous fluid.

A new very high-pressure natural polymorph of SiO_2 from the Muonionalusta meteorite

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Keywords: SiO_2 natural high-pressure polymorph, Muonionalusta meteorite.

Silicon dioxide (SiO_2) is a major component of terrestrial planets and dominates nearly all geological environments. Until now, six natural SiO_2 polymorphs were known: quartz, tridymite, and cristobalite (stable at low pressure), coesite (high pressure), stishovite and seifertite (very high pressure). We report the discovery of a seventh natural polymorph, currently under IMA-CNMNC approval, found in the Muonionalusta meteorite – an iron meteorite of the IVA group with a terrestrial age over 0.8 Ma (Norrbotten, Sweden). This meteorite is thought to have formed during a shock event that generated pressures up to ~40 GPa. The new SiO_2 polymorph occurs in unoriented silica veins (1.2–15 mm long, 0.6–2 mm wide), intergrown with stishovite and hosted in a matrix of kamacite and troilite, with minor taenite and schreibersite. It forms nanocrystalline aggregates (~7 nm), appearing brighter than stishovite in backscattered electron images and exhibiting distinct Raman spectra compared to all known silica polymorphs. WDS electron microprobe analysis across 13 points confirms a nearly pure SiO_2 composition, with trace Fe and Al substitution, yielding the formula $(Si_{0.999}Fe_{0.001}Al_{0.001})O_2$. Indexing and Pawley fitting indicate a monoclinic unit cell (space group $P2_1/c$; Z = 6) with parameters consistent with a synthetic SiO_2 phase quenched from ~45 GPa under quasi-hydrostatic conditions. Rietveld refinement, based on a theoretical model (Teter et al., 1998), gives: a = 7.657(3) Å, b = 4.091(2) Å, c = 5.016(3) Å, β = 118.21(6)°, and V = 138.44(14) Å³. The structure is built from kinked, edge-sharing SiO_6 octahedra aligned along [101] in the (010) plane and stacked in alternating layers via $c/2$ translation. This forms a dense framework distinct from those of stishovite and seifertite. Thermodynamic analysis based on molar volume (stishovite: 14.037, seifertite: 13.988, the new SiO_2 polymorph: 13.894 cm³/mol) supports that the new polymorph is the densest – and therefore most stable – SiO_2 phase at ultra-high pressures. Its estimated stability field ranges from ~45 GPa to > 130 GPa at ~2500 K, consistent with dynamic shock conditions.

Teter D.M. et al. (1998) - High pressure polymorphism in silica. Phys. Rev. Letters, 80, 2145-2148, https://doi.org/10.1103/PhysRevLett.80.2145.

Focus stacking photomicrography: a tool for Earth sciences

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Keywords: photography, focus-stacking, high-resolution.

Petrological micrographs taken under plane-polarized light (PPL) and cross-polarized light (XPL), along with scanning electron microscope (SEM) images, are well-established tools in the earth sciences for the detailed documentation and secondary inspection of geological samples. However, optical photomicrography (particularly the focus-stacking photo technique) remains an underutilized and underestimated tool, with a limited integration into routine laboratory workflows and scarce representation in scientific literature. Indeed, the focus-stacking photographic technique enables the evaluation of three-dimensional features (not emphasized in traditional flat thin-section photographs) while preserving the ability to assess color and transparency of the samples (key aspects that are not captured in SEM images). Furthermore, the use of high-resolution instruments enables the evaluation of advanced three-dimensional features in the range of tens to hundreds of microns, such as morphological characteristics (e.g., habit and twinning) and micro-inclusions, while also allowing relatively large fields of view to be examined without loss of micro-scale information. From this perspective, the lack of high-definition photomicrographic documentation – for example in a new mineral description – seems to be an underrated yet important omission concerning the morphology and appearance of the samples. This work presents one possible macro/micro photographic setup and provides examples of the extreme magnification achievable within the visible-light wavelength range.

Chrysoberyl from the Sabatini Volcanic Complex (Latium, Italy): chemical and petrological peculiarities

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Keywords: chrysoberyl, iron-rich, metasomatism.

We present the first occurrence of chrysoberyl ($BeAl_2O_4$) found in some rare volcanic ejecta from the Sabatini Volcanic Complex (central Italy), representing the most iron-rich variety ever reported, containing up to 0.31 Fe atoms per formula unit (up to 17.24 wt.% as Fe_2O_3). Chrysoberyl occurs as yellow to brown crystals, up to 2 mm in size, typically twinned, and occasionally exhibiting penetration twinning with a pseudohexagonal habit. Refined unit-cell parameters are a = 9.4507(5) Å, b = 5.4975(3) Å, c = 4.4364(2) Å, V = 230.49(2) Å^3. Its crystal structure has been refined in *Pnma* space group down to $R1$ = 0.0397 for 420 unique reflections with $F > 4\sigma(F)$ and 41 refined parameters. The structural formula of the refined sample is $^{Be}Be^{Al(1)}Al^{Al(2)}(Al_{0.85}Fe^{3+}_{0.15})$ (Z = 4).

A comparison of this atypical occurrence with those previously reported in the literature has revealed several peculiarities, allowing for the inference of important mineralogical information.

Among the worldwide occurrences of chrysoberyl (YinCe et al., 2022), the studied sample exhibits the largest unit-cell parameters observed in nature to date, attributed to chemical expansion resulting from Fe-to-Al substitution in the Al(2) site. Moreover, a comparison of the lattice parameters and Fe_{tot} content of the Trevignano chrysoberyl with literature data, including experimental results on Fe-doped synthetic chrysoberyl reveals a clear positive linear correlation between cell dimensions and Fe^{tot} content.

A comparison between the thermal expansion of chrysoberyl (Hazen & Finger, 1987) and the refined structure highlights how the differential chemical expansion resulting from Fe-to-Al substitution at the unique Al(2) site differs from the isotropic expansion induced by increasing temperature, producing a notable degree of structural deformation.

The absence of typical chrysoberyl-associated minerals (Franz & Morteani, 1984), particularly quartz and beryl, suggests a distinctive minerogenesis, likely involving direct crystallization from a fluid-rich environment. Textural, optical, and chemical evidence supports a hybrid igneous-metasomatic origin, driven by high temperatures and pervasive fluid circulation.

Since this geological environment and its peculiar genetic process appear capable of accommodating significantly higher amounts of metals — and given the industrial, medical and military relevance of metal-rich chrysoberyl in laser applications — further investigations are recommended to clarify the origin of this anomaly.

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Hazen R.M. & Finger L.W. (1987) - High-temperature crystal chemistry of phenakite (Be_2SiO_4) and chrysoberyl ($BeAl_2O_4$), Phys. Chem. Minerals, 14, 426-434, https://doi.org/10.1007/BF00628819.

YinCe M. et al. (2022) - Types and genetic mechanism of chrysoberyl deposits, Acta Petrol. Sinica, 38, 943-962, https://doi.org/10.18654/1000-0569/2022.04.01.

Zunyite, $Al_{13}Si_5O_{20}(OH,F)_{18}Cl$, from Larak Island (Iran): mineralogical insights

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Keywords: zunyite, chemical zoning, crystal growth.

Zunyite, $Al_{13}Si_5O_{20}(OH,F)_{18}Cl$, is a rare aluminosilicate with a framework consisting of Si_5O_{16} pentamer unit and Al-octahedra (Zhou et al., 2003). The crystal structure of this mineral was refined by Kamb (1960) and then reported in few other works (Louisnathan & Gibbs, 1972; Baur & Ohta, 1982; Zhou et al., 2003) where particular focus was addressed to the degree of Al-Si and F-OH atomic order. Nuclear magnetic resonance evidenced that the number of Al-octahedra with one F atom increases with F content, whereas the number with two F atoms remains negligible, indicating that F preferentially occupies AlO_4OHF octahedra (Zhou et al., 2003).

In the present study, zunyite from the Larak island at the north of the Strait of Hormuz (southern Iran) was investigated by combining single crystal X-ray diffraction (SCXRD), secondary electron microprobe (SEM) and electron backscatter diffraction (EBSD). The mineral occurs as euhedral crystals, twins, monomineralic clusters and matrix specimens associated with hematite and fluorite. Grayish-red and yellow single crystals of zunyite were selected for SCXRD analyses. They crystallize in the *F*-43*m* space group and exhibit lattice constant *a* varying from 13.8566(2) to 13.8679(2) Å and volume, *V*, in the range 2660.5(1)-2667.0(1) $Å^3$. The obtained value of the *a* parameter indicates a Si content (4.8-5.0 a.p.f.u.) which is close to that found for zunyite from Arizona (Baur & Ohta, 1982). Inclusions of quartz, hematite and rutile as well as chemical zoning of fluorine both in single crystals and twins were detected through SEM observations. Preliminary hints on the zunyite crystal growth were also derived by EBSD data.

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Color mechanisms in natural and heated Paraíba tourmalines from Mozambique

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Keywords: tourmaline, thermally treated, spectroscopic analyses.

Mineralogy plays a vital role in understanding the properties of minerals, including color, a determining factor in the commercial value of gems. For this reason, laboratory treatments to modify color are widely used. Tourmalines, chemically complex borosilicates, represent a key example of mineral color variability, showing hues across the entire visible spectrum (Bosi, 2018**).** The most prized tourmaline variety is Paraíba, known for vivid turquoise to neon blue color due to the presence of Cu **(**hundreds of ppm), with Fe below 1 wt% (Katsurada et al., 2019). This rare Cu-bearing tourmaline, sourced from Brazil, Nigeria and Mozambique, can reach prices of USD 50,000 per carat (Pezzotta & Laurs, 2011). Transition metals like Ti, V, Cr, Mn, Fe and Cu occupy octahedrally coordinated sites in the tourmaline structure and act as chromophores, influencing hue and saturation (Pezzotta & Laurs, 2011). Defects caused by impurities and polyhedral distortions may also affect perceived color (Li et al., 2018). Understanding natural and treatment-induced color causes are critical to distinguishing treated from natural gems, still an open challenge in tourmaline crystal chemistry. In this study, over 40 Cu-bearing tourmalines of various colors from Mavuco (Mozambique), the world's largest alluvial deposit of cuprian tourmalines, were heated in controlled atmospheres. Colors were classified using the Munsell system in transmitted and incident light, along both **a** and **c** axes, before and after heating. Samples with enhanced neon-blue tones and representatives of other hues were characterized via electron microprobe analysis, optical absorption spectroscopy and Fourier-transform infrared spectroscopy. These Paraíba samples showed elbaitic to liddicoatitic compositions, with color driven by the combination, concentration and oxidation state of Cu, Mn, Fe, and Ti. Purple and bicolored (purple and grayish blue) samples shifted most effectively toward neon blue after heating, due to Mn^{3+} reduction to Mn^{2+}. In samples with low Ti and Fe content, Cu^{2+} absorption dominates, yielding neon-blue hues. Conversely, with high Ti and Fe contents, green tones emerge. Green tourmalines heated up to 600 °C showed slight shifts toward yellowish green tones, due to Mn^{2+}–Ti^{4+} absorption. Further analyses, including single-crystal X-ray diffraction and electron paramagnetic resonance spectroscopy, will refine the crystal-chemical model of color origin in natural and heated Cu-bearing tourmalines. A similar approach was recently successfully applied to the colorless neotype elbaite from Elba Island, to study its transition to red rubellite by irradiation and back to colorless by heating. The high-resolution model will clarify neon-blue color mechanisms and support an analytical protocol linking color evolution to chemical composition and treatment conditions. This could help differentiate treated from natural gems, contributing to greater transparency and regulation of the gem market.

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Katsurada Y. et al. (2019) - Geographic Origin Determination of Paraíba Tourmaline. Gems Gemol., 55, 648-659, https://doi.org/10.5741/GEMS.55.4.648.

Li M. et al (2018) - The Chemical States of Color-Induced Cations in Tourmaline Characterized by X-Ray Photoelectron Spectroscopy. J. Spectr., 2018(1), 3964071, https://doi.org/10.1155/2018/3964071.

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Definition of neotype material of the hydrocarbon mineral simonellite, $C_{19}H_{24}$

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Keywords: polycyclic aromatic hydrocarbon minerals, simonellite, crystal structure.

Polycyclic Aromatic Hydrocarbon (PAH) minerals are very rare and only eleven species belonging to this group are currently known. Several of them (7 out of 11) were described before the establishment of the Commission on New Minerals and Mineral Names of the International Mineralogical Association in 1959 and before the routinary preservation of type material. In the last 35 years the type material of two PAH minerals from Tuscany have been redefined, i.e., those of dinite, $C_{20}H_{36}$, from Castelnuovo di Garfagnana (Lucca Province) (Franzini et al., 1991) and branchite, $C_{20}H_{34}$, from Monte Vaso (Pisa Province) (Bonaccorsi et al., 2024). A third Tuscan PAH mineral is simonellite, $C_{19}H_{24}$, first described from the lignite deposit of Fognano, near Montepulciano (Siena Province) (Boeris, 1919).

Notwithstanding several studies on this species mainly performed in the 1960s on synthetic recrystallized specimens, no type material has never been reported. Following a new find of simonellite at its type locality by the mineral collector M. Bonechi, simonellite was reexamined using single-crystal X-ray diffraction on natural crystals. Simonellite is orthorhombic, space group *Pnaa*, with unit-cell parameters $a = 9.2220(5)$, $b = 9.1269(5)$, $c = 35.8907(17)$ Å, $V = 3020.9(3)$ Å^3. Its crystal structure was refined to $R1 = 0.0512$ for 2721 unique reflections with $Fo > 4\sigma(Fo)$ and 244 refined parameters. Simonellite is a molecular solid and corresponds to 1,1-dimethyl-1,2,3,4-tetrahydro-7-isopropylphenantrene. Since no type material for this species was known, the studied sample was proposed as neotype specimen and the proposal was accepted by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (Nomenclature Voting Proposal 24-F). The neotype of simonellite is deposited in the mineralogical collection of the Museo di Storia Naturale of the University of Pisa under catalogue number 20079.

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Franzini L. et al. (1991) - Re-discovery and re-definition of dinite, $C_{20}H_{36}$, a forgotten organic mineral from Garfagnana, northern Tuscany, Italy. Eur. J. Mineral., 3, 855-861, https://doi.org/10.1127/ejm/3/5/0855.

(V,Cr)-rich grossular from the Peloritani Mountains, (northeastern Sicily, Italy): occurrence and crystal structure

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Keywords: (V-Cr) rich grossular, Peloritani Mountains, crystal structure.

During the last five years, field sampling was conducted in some mineralized outcrops of the Peloritani Mountains, northeastern Sicily (Italy), in order to improve the mineralogical knowledge of this area, allowing the findings of arsenate assemblages and the redefinition of chukhrovite-(Ce) (Mauro et al., 2023, 2025).

Following the paper by Baldanza (1958), field collecting was performed also in the Vallone d'Armi, Fiumedinisi, Messina Province, where some erratic blocks composed by aggregates of prismatic crystals of pyroxenes, up to 10 cm in length, dark green in colour, were identified. A more careful observation of these blocks allowed to identify some druses showing euhedral prismatic green crystals belonging to the diopside-hedenbergite series, up to 2 cm in length, associated with massive white calcite, orange garnets, creamy yellow titanite and some olive-yellow crystals belonging to the epidote-clinozoisite series. Moreover, emerald-green equant anhedral crystals of garnet, up to 3 mm in size, embedded in the host rocks, associated with hedenbergite, epidote, graphite, and quartz, were observed.

Back-scattered electron images of this garnet revealed its compositional inhomogeneity, with two different domains, having different (V+Cr)/Al atomic ratios. Electron microprobe data indicated the chemical formula $^{X}(Ca_{2.86}Fe^{2+}_{0.08}Mn_{0.06})_{\Sigma=3.00}$ $^{Y}(Al_{1.56}Fe^{3+}_{0.32}Ti_{0.05}Fe^{2+}_{0.05}V_{0.01})_{\Sigma=1.99}(SiO_4)_{2.96}[(OH)_{0.08}F_{0.07}]$ for the (V,Cr)-poor domain and $^{X}(Ca_{2.92}Mn_{0.03}Fe_{0.03}Y_{0.01})_{\Sigma=2.99}$ $^{Y}(Al_{0.74}V^{3+}_{0.64}Cr_{0.61}Ti_{0.02})_{\Sigma=2.01}(SiO_4)_{2.98}[F_{0.07}(OH)_{0.01}]$ for the (V,Cr)-rich domain, respectively. The chemical composition of this latter domain is noteworthy, corresponding to an intermediate member between grossular, goldmanite, and uvarovite. Such a variety is known with the trade name of "tsavorite". Single-crystal X-ray diffraction study was performed on the (V,Cr)-rich domain, giving unit-cell parameters a = 11.9747(5) Å, V = 1717.1(2) Å^3, space group Ia-3d. The crystal structure was refined to R_1 = 0.0165 for 234 unique reflections with $F > 4\sigma(F)$ and 20 least-square parameters. The cation distribution proposed on the basis of chemical data is fully confirmed. The genesis of "tsavoritic" garnets from the Fiumedinisi area is discussed.

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Mauro D. et al. (2023) - Occurrence and crystal chemistry of austinite, conichalcite and zincolivenite from the Peloritani Mountains, northeastern Sicily, Italy. Mineral. Mag., 87, 659-669, https://doi.org/10.1180/mgm.2023.49.

Mauro D. et al. (2025) - Chukhrovite-(Ce), $(Ca_3Ce)[AlF_6]_2(SO_4)F\cdot 12H_2O$, from the Tripi mine, Alì, Messina Province, Sicily, Italy: definition of neotype material. Mineral. Mag., https://doi.org/10.1180/mgm.2024.91.

A multi-scale approach to partially crystalline gem materials: unravelling the complexity of chrysocolla

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Keywords: chrysocolla, short-range order, nanoscale characterization.

Partially crystalline materials used in gemmology include a wide range of mineral species with distinctive compositional and structural properties, influencing their appearance, durability, and aesthetic value. A notable example is chrysocolla, classified as a hydrated copper silicate ($Cu_{2-x}Al_x(H_{2-x}Si_2O_5)(OH)_4 \cdot nH_2O$; $x < 1$) (Dold et al., 2023) and compositionally described as a colloidal system of hydrated silica and copper oxides. Chrysocolla occurs in various colours influenced by impurities and, in its blue-green hues, has been valued since antiquity as a pigment and, in jewellery, as a gem material for amulets and ornaments. Due to its intense colouring and unique aesthetic aspects, it remains widely appreciated in gemmology today. Chrysocolla was officially recognised as a mineral species by the International Mineralogical Association (IMA) in 1969. However, its nature remains debated, as it is still unclear whether it constitutes a distinct mineral phase, an aggregate of several phases, or a colloidal gel. Research has often produced discordant results due to its inherent complexity and pseudo-amorphous character, which make it analytically challenging (Frost et al., 2012) and unstable under certain conditions. These aspects complicate its identification and classification in mineralogy and gemmology.

This study aimed to characterise chrysocolla in terms of composition, mineralogy and microstructure, through a multi-methodological approach. To this end, an *ad hoc* analytical protocol was developed to highlight the peculiarities of the material without compromising its stability. Distinctive aspects of chrysocolla not previously observed were reported for samples from two mining localities — Capo Calamita, Capoliveri (Italy), and Cornwall (Lebanon County), Pennsylvania (USA) — which were investigated using both conventional and high-resolution techniques. Particular focus was placed on chemical composition, through point and spatial surveys employing electron microprobe analysis with wavelength-dispersive spectroscopy (EMPA-WDS). Multivariate analysis of the data allowed for the identification of relationships between compositional variability and formation conditions. The local atomic arrangement was studied using the Pair Distribution Function (PDF) analysis based on synchrotron radiation data, giving new insights into bond distances and structural coherence. Given the partially crystalline nature of chrysocolla, in which distinctive properties are manifested at the level of local domains, the investigation was extended to the nanoscale using transmission electron microscopy (TEM). The results provided new insights into the compositional, microstructural, and textural properties of chrysocolla, helping to better define its distinctive characteristics. Moreover, the study introduced new methodological approaches for its recognition and classification, with significant implications in both mineralogical and gemmological fields.

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Frost R.L. et al. (2012) - Thermogravimetric analysis, PXRD, EDX and XPS study of chrysocolla $(Cu,Al)_2H_2Si_2O_5(OH)_4 \cdot nH_2O$ structural implications. Thermochim. Acta, 545, 157-162, https://doi.org/10.1016/j.tca.2012.07.011.

Natural versus artificial: exploring the exotic mineralogy of fulgurites

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Keywords: fulgurite, reduced phases, phosphides.

Fulgurites form as glassy rocks when electrical discharge travels through a target material. They are named after *fulgur*, the Latin word for lighting, but the definition of fulgurite can include artificial discharge sources and targets materials not typically found in nature (Pasek & Pasek, 2018). Thus, a fulgurite is artificial when formed by a non-natural source, such as a downed power line, and anthropogenic if the target material contains human-made components, like a metal conductor (Pasek & Pasek, 2018). Natural fulgurites are well known to show an unusual mineralogy, depending on the composition of the target materials by the high temperature reached during the discharge, a few to tens of thousands of degrees (Essene & Fisher, 1986). Fulgurites usually contain minerals strictly related to a highly reducing environment such as metallic silicon, iron-silicon alloys, silicides and phosphides (Essene & Fisher, 1986). Even more exotic phases have been reported in fulgurites, comprising a quasicrystal (Bindi et al., 2023). Artificial and anthropogenic fulgurites are far less investigated than natural ones, even if a more systematic characterization could provide useful information to help identify the origin of the material, which is not often straightforward to determine, and could potentially provide forensic evidences in case fires when the fall of a power line or of a lightning strike might be involved (Pasek & Pasek, 2018). Furthermore, artificial and anthropogenic fulgurites might show a different morphology and mineralogy with respect to natural ones, depending on the composition of the target materials and the temperature reached during the discharge (Pasek & Pasek, 2018), thus a systematic characterization could provide diagnostic evidence to discriminate the origin of a fulgurite. In this contribution we describe and compare two fulgurites, one from Seffner (FL, USA), whose origin is undoubtedly artificial, and a natural one, from Mount Belmont (MT, USA), of natural origin. The samples were characterized by semi-quantitative Energy Dispersion Spectroscopy (EDS) and Electron Back-Scatter Diffraction (EBSD) in a Scanning Electron Microscope (SEM). As expected both samples contain reduced phases, such as phosphides and silicides, with the peculiar occurrence of Al-Fe-Si compounds in the artificial samples, related to the presence of a metal conductor. A thorough characterization of the latter compounds together with silicides could provide pivotal information for the identification of the natural or artificial origin of fulgurites.

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Essene E.J. & Fisher D.C. (1986) - Lightning Strike Fusion: Extreme Reduction and Metal-Silicate Liquid Immiscibility. Science, 234, 189-193.

Bindi L. et al. (2023) - Electrical discharge triggers quasicrystal formation in an eolian dune. Proc. Natl. Acad. Sci. USA, 120, e2215484119.

Nanoscale analysis of Red Muds from Portovesme (Sardinia)

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Keywords: bauxite residues (red muds), Sardinia, TEM

At the Porto Vesme disposal site in southern Sardinia, Italy, about 30 million tonnes of bauxite residues from aluminium extraction using the Bayer process are stored. The mineralogical and geochemical features of these residues have recently been investigated, also to assess the economic viability of extracting rare earth elements (REEs) and other valuable elements, such Ga, Sc, V (Mameli et al., 2025; Schingaro et al., 2025). The samples mineralogy includes hematite, goethite, ilmenite, gibbsite, boehmite, bayerite, anatase, rutile, quartz, sodalite, cancrinite, andradite, calcite, dolomite, halite. Lanthanides-rich phosphate minerals as well as LREE ferrotitanates were sporadically observed. The samples chemistry provides Fe_2O_3, Al_2O_3, SiO_2, Na_2O, TiO_2 and CaO in order of abundance but also relevant concentrations of Zr, Cr, Ce, V, Sr, Ni, Zn, Ga and Y. The REEs are enriched relative to the parent material with LREEs > HREEs+Y and Sc. Ce is the most abundant LREE and the chondrite normalized patterns show significant positive Ce anomalies. However identification of REE/valuable elements bearing phases in bauxite residue is not a trivial task and necessitates investigation at the nanoscale.

Preliminary results of TEM analyses have revealed the abundant presence of Fe-Ti oxides bearing Ca, Cr and LREE with laminar habit and lattice fringes spacing around 2.70 Å which can correspond with a ferrotitanate phase. EDS identification of the precise ferrrotitanate composition is difficult because of the LREE, Ti, and Cr intense and complex X-ray energy overlaps in the 4.5 to 6 keV spectral interval, especially when Ti has high concentration (Lacinska et al., 2021). However, detailed EDS analyses allowed the identification of a well defined peak for the Lα line of La (4.65 keV), slightly overlapped with Ti Kα line (4.52 keV). Ce was identified by the Ce Lβ line at 5.26 keV, given that Ce Lα line (4.84 keV) was usually hidden by the Ti Kβ line (4.93 keV). Cr was easily identified by its Cr Kα line (5.41 keV).

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Mameli P. et al. (2025) - Distribution and fractionation of Rare Earths (La–Lu, Sc, Y) and other critical metals in bauxite residues: addressing the profitability of the red muds stored at the Porto Vesme disposal site, Sardinia Island, Italy. J.Geochem. Explor., 275, 107792, https://doi.org/10.1016/j.gexplo.2025.107792.

Schingaro E. et al. (2025) - Exploring the potential of red muds from Portovesme (SW Sardinia, Italy): Multiscale analysis of REEs content and mineralogy. Heliyon, 11, e43303, https://doi.org/10.1016/j.heliyon.2025.e43303.

Prelude to the establishment of the crichtonite group: crystal-chemical intricacies and end-member formulae

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Keywords: crichtonite group, mineralogical systematics, crystal-chemical formulae

As of today the crichtonite group includes 19 minerals. The eponymous mineral crichtonite was described at the beginning of the XIX Century as a titaniferous oxide of iron (de Bournon, 1814). Today the mineral is known to contain also strontium, but its presence was initially overlooked. Senaite was described at the end of the XIX Century as an oxide of lead, titanium and iron (Hussak & Prior, 1898). Both crichtonite and senaite were originally considered as variants of ilmenite. After the solution of the structure of crichtonite (Grey et al., 1976) those mineral were assigned the general formula $AM_{21}O_{38}$. Later on, that formula was refined as $^{M0}A^{M1}B^{M2}C_2^{M3\text{-}M4\text{-}M5}D_{18}O_{38}$, where the M0 site is XII-coordinated and all the other sites are VI-coordinated but M2 which is IV-coordinated.

Up to 1982 new minerals of the crichtonite group were established based on the dominant *A* cation: Sr in crichtonite (1814), Pb in senaite (1898), REEs in davidite (1906: after the Levinson suffixes came into use two distinct minerals, davidide-(La) and davidite-(Ce), were approved), Na in landauite (1965), Ca in loveringite (1977), Ba in lindsleyite (1982), K in mathiasite (1982).

Starting from 1994 other crichtonite-group minerals were approved: in most cases their uniqueness was assessed based on the dominant constituent at other sites besides M0: $^{M0}Sr^{M1}Y$ in dessauite-(Y) (1994; crichtonite has $^{M0}Sr^{M1}Mn$), $^{M0}Pb^{M1}U$ in cleusonite (1998; senaite has $^{M0}Pb^{M1}Mn$), $^{M0}Pb^{M1}U$ in gramaccioliite-(Y) (2001), $^{M0}Pb^{M1}Mn^{M2}Mn^{M3\text{-}M4\text{-}M5}V$ in paseroite (2011; senaite has $^{M2}Fe^{M3\text{-}M4\text{-}M5}Ti$), $^{M0}Pb^{M1}Mn^{M2}Zn$ in almeidaite (2013), $^{M0}Sr^{M1}U$ in mapiquiroite (2011), $^{M0}\square$ in mianningite (2014), $^{M0}Sr^{M1}Fe$ in botuobinskite (2018), $^{M0}Sr^{M1}Zr$ in mirnyite (2018), $^{M0}REE^{M1}U$ in haitaite-(La) (2019; davidite-(La) has $^{M0}REE^{M1}Y$), $^{M0}Sr^{M1}Ca$ in saranovskite (2020).

However, the partition of cations among the various sites of crichtonite-group minerals is far from being well assessed. In most cases the site population may be constrained a bit based on single crystal structural data, by considering the overall site scattering at each site, but in cases of complex chemical compositions there are considerable degrees of freedom in doing that. In some cases spectroscopic data would be necessary to define the oxidation state of some cations, *e.g.* V^{3+} *vs* V^{5+} in paseroite, or Fe^{2+} *vs* Fe^{3+} in saranovskite. Some $(OH)^-$ may substitute for O^{2-}, and this adds uncertainty in the recalculation of formulae based upon charge balance. Moreover minor vacancies may occur at some sites, and this further increases the variance of the system. As a consequence in the IMA List of Minerals the chemical formulae of the 19 crichtonite-group minerals are given with as many as four chemical elements within the same brackets. We will try to define thumb rules for partitioning cations among the different sites and write end-member formulae for all minerals of the crichtonite group.

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Crystal chemistry of clinopyroxenes enclosed in mantle xenoliths from Assab (Ethiopia)

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Keywords: mantle xenoliths, clinopyroxenes, petrological implications.

The Assab volcanic region (Ethiopia) presents the opportunity to study a rift zone, from continental rift to ocean floor spreading. In this region, peridotitic nodules, enclosed in basaltic lavas, represent portions of the upper mantle torn off during the ascent of magma. They are fundamental for the knowledge of the upper mantle and of the phenomena that occurred, such as partial melting or re-equilibration under variable conditions of temperature and pressure. In the Assab volcanic province, nodules with variable compositions span from harzburgite, spinel lherzolite to spinel-plagioclase peridotite, pyroxenite, and gabbro (Teklay et al., 2010). The peridotitic nodules, which present the typical 4-phase assemblage of olivine, orthopyroxenes, clinopyroxenes, and spinel, have been investigated by various authors, in particular with regard to geochemistry and petrology. Unfortunately, there are few studies on the crystal chemistry of the phases present, among these the characterization of olivine in geo-thermometric function using the distribution coefficient K_D of Fe and Mg between non-equivalent structural sites M1 and M2 (Basso et al., 1979). Another investigated phase was the spinel, always for the purpose of the distribution of elements, such as Mg and Al between the T and M sites and the influence on the oxygen coordinate (Princivalle et al., 1986). However, there are no works on the crystal chemistry of pyroxenes, in particular clinopyroxenes, although these phases have provided important information not only on geo-thermometry, but also on geo-barometry. The latter was estimated using the relation between cell volume (V_{cell}) versus site volumes (V_T-V_{M1}-V_{M2}) (Nimis, 1995). In addition, the determinations of pressure and temperature have been made considering the chimismus of both single clino-pyroxene from peridotitic rocks and also using the couple clino- and ortho-pyroxene (Teklay et al., 2010 and references therein).

In this work, clinopyroxenes from 3 Assab nodules were considered, and their structure was carried out by single crystal X-ray diffraction, while the chemistry of the same crystals used for XRD was determined by electron microprobe. The results were compared with those of other cpx series of spinel peridotites from various parts of the world as well as with cpx included in sp-pl and sp-gt peridotites. From these comparisons, unlike other series in which there is a pressure differentiation, the three Assab samples are distributed in the spinel peridotite field at variable pressure conditions estimated between 20 and 14 kbar. As a conclusion, it can be hypothesized that the basaltic lavas sampled different portions of the lithospheric mantle during the magma ascent.

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Nimis P. (1995) - Clinopyroxenes from plagioclase peridotites (Zabargard Island, Red Sea) and comparison between high- and low-pressure mantle clinopyroxenes. Mineral. Petrol., 53, 49-61.

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Pink tourmalines from three distinct Pegmatite provinces: crystal chemistry and genetic implications

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Keywords: tourmaline, crystal chemistry, genetic implications.

Borosilicate minerals of the tourmaline supergroup are valuable both for collectors and for geological research, as their chemical composition reflects the growth-medium conditions and their evolution (Bosi, 2018). Tourmalines show a wide compositional variability and display a remarkable range of colors, including red, pink, yellow, orange, green, blue, violet, brown, and black. They are often chemically zoned (Agrosì et al., 2006), and a single crystal may exhibit a wide range of appealing colors (Rizzo et al., 2023).

In this study, a structural and chemical characterization of pink tourmalines from different mines is carried out to define if the pink color could be related to similar growth conditions. Samples from Cruzeiro (Brazil), Nuristan (Afghanistan), and Malkhan (Russia) were studied using Electron Microprobe Analysis, Micro Laser Induced Breakdown Spectroscopy (LIBS), and Single Crystal X-ray Diffraction. The results show that the pink tourmalines are Mn-rich elbaite, with the pink coloration linked to Mn at the *Y* site, indicating crystallization from Mn-rich pegmatitic fluids. LIBS spectra suggest a Li-rich pegmatite origin. Nevertheless, the studied pink tourmalines show also some differences: the sample from Cruzeiro exhibits strong chemical zoning, that from Nuristan has a uniform composition, and the tourmaline from Malkhan shows slight zoning with high F content. A comparison with a pink tourmaline from Anjanabonoina (Madagascar) (Rizzo et al., 2023) reveals that it is Ca-rich, belonging to the calcic group and crystallizing in an open system influenced by external Ca-rich fluids, contrasting with the closed system of the samples from Cruzeiro and Nuristan (Rizzo et al., 2025). The sample from Malkhan shows an anomalous chemical variation of Ca and requires further investigation.

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Bosi F. (2018) - Tourmaline crystal chemistry. Am. Mineral., 103(2), 298-306, http://doi.org/10.2138/am-2018-6289.

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Zunyite from Qalat-e Payeen salt dome at the Hormuz Complex (Southern Iran): mineralogy and geochemistry

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Keywords: Hormuz salt diapir, zuniyite, crystal chemistry.

The Hormuz Island is a salt diapir located at the north of the Strait of Hormuz in Iran, between the Persian Gulf and the Gulf of Oman. It consists of concentric evaporitic layers with igneous and sedimentary inclusions resulting from multiple geological processes including diagenesis, volcanism-magmatism, sedimentation-evaporation, metasomatism, and weathering (Bosák et al., 1998). The interest for the Hormuz Complex was mainly related to oil exploration (Bosák et al., 1998) although it hosts several interesting and fascinating mineral sites (Hairapetian et al., 2020). Due to its complex geological history, the definition of the chronological and genetic relations of the rock outcrops in the Hormuz Complex is very difficult. In addition, little is known on the mineralogy and geochemistry of the salt diapirs (Hassanlouei & Rajabzadeh 2019; Hairapetian et al., 2020). The Qalat-e Payeen salt dome consists of altered and fractured rhyolitic to rhyodacitic rocks, tuffs, ignimbrite and carbonate beds (limestone, dolomitic limestone, and dolostone). These rocks are heavily and highly fractured and contain fluorapatite, fluorite, hematite, zunyite, and cubes and pyritohedra of limonite after pyrite (Hairapetian et al., 2020). Zunyite is a rare and complex halide-bearing aluminosilicate mineral with the chemical formula $Al_{13}Si_5O_{20}(OH,F)_{18}Cl$. Specimens of zunyite crystals in their rock matrix from Qalat-e Payeen were here studied by combining electron micro-probe (EMP), secondary electron microscope (SEM) Raman spectroscopy and single crystal X-ray diffraction (SCXRD) in order to draw mineralogical and geochemical inferences.

The studied red euhedral crystals of zunyite exhibit cubic symmetry with a space group of *F*-43*m*, and *a* =13.8816(2) Å. The structure refinement converged at R = 1.94%, Rw = 3.20%. The crystals show optical zoning which correspond to bands of hematite inclusions as provided by SEM-BSD observations. Zunyite also contains quartz and phosphate inclusion and is embedded in a matrix with gypsum, calcite and rutile.

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Tl^+ incorporation in hydropyrochlore and hydrokenopyrochlore: Insights into the reaction kinetics

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Keywords: pyrochlores, monovalent thallium, environmental mineralogy.

Hydrated members of the pyrochlore supergroup (space group Fd–3m, Z = 8, general formula $A_{2-m}B_2X_{6-w}Y_{1-n}$; Atencio et al., 2010; Atencio, 2021), such as hydropyrochlore and hydrokenopyrochlore, are promising candidates for monovalent thallium sequestration due to their high ion-exchange potential, with interesting environmental implications (Zoppi, 2004; Taddei et al., 2024). This property arises from the peculiar structure of pyrochlore minerals, which consists of i) a framework of corner-linked BX_6 octahedra that forms tunnels along the [110] direction, and ii) the "intra-framework" sites A and Y, which are located at the center of the tunnels and are particularly susceptible to ion-exchange reactions.

In this study, the kinetics of Tl^+ incorporation into single crystals of hydropyrochlore and hydrokenopyrochlore from the Lueshe carbonatite (D.R. Congo) was investigated through a series of progressively longer imbibition experiments in Tl^+-rich aqueous solutions (1 M and 0.1 M concentrations). Structural (single-crystal XRD) and chemical (electron microprobe) analyses were performed before and after each experiment to evaluate crystal-chemical changes following the incorporation of Tl^+.

The results show that Tl^+ rapidly enters the tunnel sites, initially distributing between A and Y, and progressively ordering at the A site with increasing treatment duration. The incorporation of Tl^+ is accompanied by systematic unit-cell expansion (mainly due to the lengthening of the A–X distances) and distinct colour changes, following a logarithmic kinetic trend. Saturation is reached within ~450 minutes, corresponding to ~1.40–1.50 Tl^+ pfu. Further soaking experiments result in minor redistribution from Y to A rather than increased uptake. Furthermore, these trends seem to be independent of Tl^+ concentration in solution, confirming the ion-exchange mechanism described by Taddei et al. (2024) which involves either $[H_2O + (OH)^-]$ or H_3O^+ hosted at the tunnel sites.

These findings confirm the high efficiency and rapid kinetics of Tl uptake in hydrated pyrochlores, although Taddei et al. (2024) observed Tl^+ release consequent to imbibition experiments carried out in deionized water on previously Tl-treated crystals, highlighting the need for further research on long-term retention mechanisms.

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Atencio D. et al. (2010) - The pyrochlore supergroup of minerals: Nomenclature. Can. Mineral., 48(3), 673-698.

Taddei A. et al. (2024) - Crystallographic insights into monovalent thallium incorporation: Exploring hydropyrochlore structure for environmental remediation. Am. Mineral., 109(11), 1913-1920.

Zoppi M. (2004) - Ossidi di Nb, Ta e Ti: processi di ricristallizzazione e relazioni cristallochimiche. Ph.D. thesis, Università di Firenze, 166 p.

Kenomicrolite, $\square_2Ta_2[O_4(OH)_2]$, the first vacancy-dominated pyrochlore-supergroup mineral from Nazareno, Minas Gerais, Brazil: crystal chemistry and ion-exchange properties

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Keywords: kenomicrolite, new mineral, Tl incorporation.

Kenomicrolite (IMA 2024–097) is a new member of the pyrochlore supergroup (general formula $A_{2-m}B_2X_{1-w}Y_{1-n}$; Atencio et al., 2010; Atencio, 2021) discovered in the Volta Grande pegmatite, Nazareno, Minas Gerais, Brazil, where it likely formed via the alteration of a Ca-Na-dominant microlite-group mineral. It forms areas (up to 200 μm) in hydrokenomicrolite octahedra, pale orange in colour, with adamantine to resinous lustre. It crystallizes in the cubic system, space group *Fd*–3*m*, with unit-cell parameter $a = 10.5911(6)$ Å. Kenomicrolite is the first pyrochlore supergroup mineral having both tunnel sites (*A* and *Y*) mainly vacant, with an ideal formula $\square_2Ta_2[O_4(OH)_2]\square$ (Taddei et al., 2025). The empirical formula, obtained by combining single-crystal X-ray diffraction and EMPA data, is $(\square_{1.61}Ba_{0.29}Ce_{0.03}U_{0.03}Pb_{0.02}Mn_{0.01}Sr_{0.01})_{\Sigma 2.00}(Ta_{1.74}Nb_{0.11}Sn_{0.08}Si_{0.05}Al_{0.01}Ti_{0.01})_{\Sigma 2.00}[O_{4.65}(OH)_{1.35}]_{\Sigma 6.00}[\square_{0.56}(H_2O)_{0.36}F_{0.07}K_{0.01}]_{\Sigma 1.00}$. Unlike hydrokenomicrolite, kenomicrolite lacks H_2O at *A* and shows limited H_2O groups at *Y*, indicating a lesser hydration degree, in agreement with FTIR data collected on both species.

The enhanced ion-exchange capacity of pyrochlores, arising from their tunnel-like structure, prompted the study of the capability of this mineral to incorporate Tl^+, a highly toxic and mobile cation. Such mechanism was explored in other species of the pyrochlore-group (Taddei et al., 2024), pointing to an exchange reaction involving either $H_2O + OH^-$ or H_3O^+, which kenomicrolite hosts in small amounts (≤ 0.36 apfu). A one-day-long imbibition experiment in a 1 M Tl^+ aqueous solution was thus performed on a kenomicrolite single crystal, leading to an increase of electrons number at *A* by ~6 e^-, indicating a limited incorporation of Tl^+ in the structure (~0.15 apfu for two *A* sites), coherently with the initial low water content. Further chemical analyses are needed to precisely evaluate the extent of the incorporation.

These new data not only extend the compositional space of the pyrochlore supergroup, but also provide additional insight into the ion-exchange capacity of these minerals. Despite the limited availability of exchangeable species within the structure, kenomicrolite shows measurable incorporation of Tl^+: this suggests that even poorly hydrated and highly vacant pyrochlores could have a role in environmentally relevant exchange reactions.

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Atencio D. et al. (2010) - The pyrochlore supergroup of minerals: Nomenclature. Can. Mineral., 48(3), 673-698.
Taddei A. et al. (2024) - Crystallographic insights into monovalent thallium incorporation: Exploring hydropyrochlore structure for environmental remediation. Am. Mineral., 109(11), 1913-1920.
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Advances in the study by LIBS of topaz from different origins

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Keywords: topaz, LIBS, trace elements

Advances in the application of Laser-Induced Breakdown Spectroscopy (LIBS) for the study of topaz ($Al_2SiO_4(F,OH)_2$) from different geological origins can contribute to improve our understanding of its compositional features. Compared to conventional methods such as electron microprobe analysis (EMPA) and LA-ICP-MS, LIBS represents a rapid, minimally invasive, and *in situ* analytical technique for multi-element detection, that can be used to distinguish topazes derived from distinct formation environments (Breiter et al., 2013; Rossi et al., 2013; Dubey et al., 2021). Actually, the different types of trace elements and their quantity, are closely linked to the formation environment. In this study, gem-quality samples from different countries and deposits were analysed by micro-LIBS. Specifically, the crystals studied are colourless or very light blue samples from Brazil, Madagascar, Mozambique, Nigeria, and Tanzania and pink, yellow, and yellow-orange samples from Brazil, Utah (USA), Nigeria, and Zambia. LIBS analyses on topaz allowed the identification of the main emission lines of many elements: in addition to the major ones (Al and Si), Li, B, Na, Cl, Mg, K, Ca, Ti, V, Cr, Mn, Fe, and Ni were identified. F and OH could not be identified due to the existing setup. From an initial comparison of the data obtained, it was noted that the presence of some light elements, such as Li and B, present in traces is particularly linked to some deposits (Hervig et al., 1987). The first results obtained demonstrate that LIBS could play a significant role in the qualitative and quantitative analyses of silicates like topaz, useful above all for identifying the provenance. Future advancements in LIBS instrumentation, together with sophisticated chemometric data processing, are expected further to improve the resolution and reliability of such provenance studies.

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$Ca_2P_2O_7$: a new mineral found in super-deep diamond from Juína, Brazil

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Keywords: super-deep diamond, phosphate mineral, Brazil.

We discovered a potential new mineral with formula $Ca_2P_2O_7$ (under voting by IMA-CNMNC), within a super-deep diamond (named RV43) from the Chapadão plateau, Mato Grosso, Brazil. The diamond host originated from heavily weathered crater-facies kimberlite, dated at 93.6±0.4 Ma by U-Pb geochronology. The new mineral is closely associated with tuite and with other mineral inclusions in the host diamond (that are not in direct contact with the new mineral) including larnite, merrillite, diopside, ilmenite, magnetite, calcite, breyite, and an unidentified phosphate phase. The mineral forms discrete crystalline inclusions, exhibiting distinct Raman spectra closely matching synthetic β-$Ca_2P_2O_7$, indicative of structural similarities. X-ray diffraction analyses, performed directly on the inclusion in situ within the diamond, define a tetragonal crystal structure (space group $P4_1$), with unit-cell parameters of a = 6.6966(16) Å, c = 24.145(11) Å, and V = 1082.8(6) Å³. These values are in excellent agreement with those reported for synthetic β-$Ca_2P_2O_7$ (Boudin et al., 1993). It is likely that the new mineral is a high-temperature and high-pressure phase from the deep Earth and could be related to the retrograde transformation of tuite, which is the highest-pressure phosphate stable up to 23 GPa (Xie et al., 2002). The discovery of this new mineral, $Ca_2P_2O_7$, as well as tuite and merrillite, will provide new insights into the Earth's deep phosphorus reservoir and the crust-mantle phosphorus cycle, an important element for life.

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Hydroxyperovskites: an overlooked group of potential functional materials

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Keywords: hydroxyperovskites, crystallography, properties.

While there is enormous interest in studying oxide perovskites with stoichiometries based upon or derived from ABO_3, including oxygen-deficient compositions and organometallics, other closely related topologies have been overlooked. Hydroxyperovskites are such a group. Their structures are perovskite-like octahedral frameworks with vacant cavity *A* sites. All oxygen atoms form hydroxyl groups and each is a donor and an acceptor of hydrogen bonds. There are fifteen naturally occurring hydroxyperovskites, all very rare, and numerous synthetic analogues. There are two stoichiometries: $BB'(OH)_6$ and $B(OH)_3$. The former consists of alternating divalent and tetravalent cations (B = Na, Mg, Ca, Mn^{2+}, Fe^{2+}, Co^{2+}, Cu^{2+}, Zn; B' = Sn, Ge, Sb^{5+}). $B(OH)_3$ structures have only trivalent cations (Al, Fe^{3+}, Sc, Ga). The properties and behaviour of hydroxyperovskite solid solutions are largely unexplored. The recent discovery of the H-deficient hydroxyperovskite nancyrossite, $FeGeO_6H_5$, (Welch et al., 2025), suggests that novel H behaviour, such as rapid proton conduction, may occur in such materials. This presentation will review the current state of knowledge about hydroxyperovskites and indicate the structural features that relate to their potential as functional materials, particularly as protonic conductors.

Welch, M.D. et al. (2025) - Nancyrossite, a new hydroxyperovskite. Mineralogical Magazine, https://doi.org/10.1180/mgm.2025.10.

S3.

Mineral physics and crystal chemistry:

crucial tools for Earth Sciences

CONVENERS AND CHAIRPERSONS

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When colour makes minerals unique: the case of the green dolomite from Malentrata (Pomarance, Tuscany, Italy)

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Keywords: crystal chemistry, dolomite, spectroscopic studies.

A peculiar green variety of dolomite has been described in several deposits across Europe, including Miemo and Malentrata (Tuscany, Italy), Tarasp (Grisons, Switzerland), and Vučkovica (Serbia). This variety has attracted the interest of researchers and collectors due to its aesthetic qualities, which have led to its use as a semi-precious gemstone. In the present study, a thorough characterization of the green dolomite sampled from the Malentrata magnesite mine (Pomarance, Tuscany, Italy) was carried out. The investigation employed a range of advanced analytical techniques, including X-ray powder diffraction (XRPD), electron probe micro-analysis (EPMA), X-ray fluorescence (XRF), X-ray absorption spectroscopy (XAS), scanning electron microscopy (SEM), differential thermal analysis (DTA/TG), optical spectroscopy (UV-Vis-NIR), and electron paramagnetic resonance (EPR) spectroscopy.

The results revealed two main features of the Malentrata green dolomite: (1) an anomalous reduction in unit cell volume, caused by an excess of small ionic radius metal cations (Mg and Fe) relative to calcium, and (2) the origin of the green color, primarily attributed to the electronic transitions of iron ions, likely in combination with those of chromium. The substitution of cations in the crystal structure leads to a reduction in unit cell volume, a feature that distinguishes this dolomite from the typical variety. The presence of Fe^{2+} and Fe^{3+} proved to be key to the green coloration, with an additional contribution from Cr^{3+}, confirming that the color is not due to a single ionic species, but rather to an interaction between various transition metal cations.

Chemical analyses showed that the green dolomite from Malentrata also contains small amounts of transition metals, including manganese (Mn), chromium (Cr), and nickel (Ni), which give the mineral additional unique characteristics. These metals are homogeneously distributed within the sample and contribute to its distinctive chemical composition, highlighting the importance of complete characterization to understand the natural variability of the material.

In conclusion, the green dolomite from Malentrata represents a material of geological and chemical interest, with distinctive optical properties. The detailed understanding of its composition and structure, achieved through a multi-method approach, paves the way for future investigations in the Malentrata area, providing a solid basis for the study of local geological processes.

Crystallography tools for Investigating mineral rheology through host-inclusion systems

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Keywords: mineral inclusion, raman, elasticity.

Understanding Earth's dynamics requires detailed knowledge of how minerals deform under varying environmental conditions. Traditional experimental approaches rely on simplified synthetic materials, limiting their applicability to natural systems, which contain structural defects and chemical complexities. We are exploring novel approaches by examining mineral inclusions trapped inside host crystals as naturally pre-stressed systems that provide valuable insights into mineral rheology. By employing Raman spectroscopy to measure residual pressures in inclusions across different temperatures and pressures, we can assess how internal stress states influence the deformation behavior of the host mineral. We will show, focusing on host-inclusion systems such as zircon and quartz trapped in garnet, how this method can offer a unique perspective on the mechanical properties of rock-forming minerals. The results have broad implications for understanding deformation in diverse geological environments, refining rheological models, and improving our interpretation of large-scale geodynamic processes.

Crystal Palace: new program for organising crystal structure data

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Keywords: mineral structures, cation ordering, parametric data.

The variation in the details of a mineral structure as a function of pressure, temperature or composition provides the fundamental data to determine the link between the crystal structures and properties of minerals. In particular, the variation of cation order as a function of annealing temperature was a major focus of the work of Chiara Domeneghetti with the aim of producing geothermometers and geo-speedometers that could be used to determine cooling rates of rocks. The organisation and analysis of crystal structure data from such a series of structure refinements is a major challenge, involving a lot of manual manipulation and copying and editing of data and structural parameters calculated with a series of programs. Use of conventional programs that handle one refined crystal structure at a time is still very time consuming and runs the risk of introducing cut-and-paste errors into final tables. And even with the development crystallographic information format (cif) files the esu's of bond lengths, angles and polyhedral volumes cannot be determined because the cifs do not contain the full variance-covariance matrix from the structure refinement, but only the uncertainties of the individual positional parameters. Crystal Palace is a new Windows program for Parametric Analysis of Least squares and Atomic Coordination with Estimated standard uncertainties. The primary purpose of the program is to organise the refined structures from parametric structural studies (as a function of P or T or a series of compositions or states of order) for analysis of the structural trends, and the production of tables for analysis and publication without the risks associated with manual editing. The program reads structural information from one or more cifs. It organises the data by finding the structurally equivalent atoms in each structure and therefore can organise structural information even if atom names or site occupancies are different, or the atom lists in the cifs are ordered differently for example as in solid solutions or between different publications.

Crystal Palace uses symmetry to estimate the covariance of structural parameters and thus the uncertainties of bond lengths, angles and polyhedral volumes (and is the first program to fully calculate esu's of polyhedral volumes). Crystal Palace also calculates various polyhedral distortion parameters and rigid-body corrections to bond lengths. The program can write new cifs and export unit-cell data and polyhedral volumes to the EosFit program to allow their thermal expansion and compressibility to be fitted with equations of state.

The program is available as freeware from www.rossangel.net

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Structural response of orthorhombic perovskites to non-ambient conditions

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Keywords: orthorhombic perovskites, non-ambient structure evolution, Ge-doped $CaTiO_3$.

Interest in $GdFeO_3$-type perovskite minerals (s.g. *Pbnm*) and their synthetic analogues spans both geophysics (*e.g.*, bridgmanite represents the predominant phase of the Earth's lower mantle) and materials science (Szuromi & Grocholski, 2017). The aristotype perovskite adopts a cubic structure (s.g. *Pm*-3*m*), with *A* cations located at the center of dodecahedral sites within a three-dimensional framework of corner-sharing BO_6 octahedra. This ideal cubic atomic arrangement is often reduced in symmetry (frequently to *Pbnm*) by a combination of octahedral tilting and distortion of the BO_6 octahedra. The interplay of chemistry and changes in octahedral tilting is key to understanding the temperature and pressure-dependent evolution and the thermodynamic state of perovskites. While a general scenario of perovskite structural evolution – based on the *A* and *B* cation charges, the relative compressibility of AO_{12} and BO_6 polyhedra, and the octahedral tilt – is consolidated in its general aspects, several specific cases show that it can be improved.

For example, besides the definition of dichotomous trends depending on the charge of *A* and *B* cations, the evolution of $GdFeO_3$ perovskites at high-pressure and high-temperature is affected whether transition metal ions are hosted at the octahedral site or not (Ardit, 2015). In other (limiting) cases, the absence of change in octahedral tilting under compression (*i.e.*, a perovskite volume reduction under pressure controlled solely by isotropic compression) gave rise to the so-called locked-tilt perovskite (Ardit et al., 2017). More recently, in search of some of these limit cases, the high-pressure and high-temperature behavior of a suite of Ge-doped $CaTiO_3$ orthorhombic perovskites has been studied and new unexpected results have been obtained. Experimental high-pressure synchrotron diffraction data coupled with density functional theory (DFT) calculations on $Ca(Ti_{0.95}Ge_{0.05})O_3$ perovskite, indicate isotropic axial compression with a modest increase in octahedral tilting with pressure, qualifying this perovskite compound as a new type of orthorhombic perovskite that exhibits both isotropic compression and non-locked octahedral tilting (Ardit et al., 2023). In situ high-temperature synchrotron diffraction data on the $CaTi_{1-x}Ge_xO_3$ (x = 0 to 0.08 apfu) reveal a giant anomaly in thermal expansion that deviates from the general linear trend defined by the $CaTiO_3$ and $CaGeO_3$ end-members. This contribution provides an overview of orthorhombic perovskite at non-ambient conditions, with emphasis on recent results on the high-temperature behavior of Ge-doped $CaTiO_3$ compounds.

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Omphacite in host-inclusion systems: a new tool for elastic geothermobarometry

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Keywords: omphacite, elastic geothermobarometry, Raman spectroscopy.

Elastic geothermobarometry uses the preserved pressures of mineral inclusions to estimate the pressure and temperature conditions at the time of their entrapment (Angel et al., 2019) and thus constrain metamorphic pressures and temperatures. Pressures of inclusions can be determined by Raman spectroscopy, provided that the pressure-induced shifts in phonon wavenumbers are well established through experimental data.

Omphacite, a common mineral found in diverse geological environments, is an ideal candidate for elastic geothermobarometry. However, because Raman scattering is highly sensitive to structural deformations, the positions of the Raman peaks of omphacites are influenced by their composition and the state of cation order. This has so far prevented omphacites from being used for elastic geothermobarometry.

In situ high-pressure Raman spectra were recently measured on both natural ordered and experimentally disordered omphacites (Baratelli et al., 2024; 2025). Two sets of Fe-poor crystals with different chemical compositions, previously studied by Boffa Ballaran et al. (1998), were used as the starting material for our study. By analysing omphacite crystals with different degrees of order, achieved via isothermal annealing experiments, we observed that increased cation disorder led to broader Raman peaks, while pressure variations altered peak positions. However, the chemical composition also influences the peak position. Therefore, Fe^{3+}-rich crystals were also analysed, as an initial step toward the chemical calibration of omphacites using Raman spectroscopy.

These data show that the most intense Raman peak at about 680 cm^{-1} has the same pressure dependence independent of composition and state of order. This peak can therefore be used to determine the residual pressure of omphacite inclusions, provided the composition is known, and this allows the calculation of the entrapment isomeke. In addition, measurement of the full width at half maximum of the same peak indicates the state of cation order, which can be used to estimate the equilibration temperature and thus the entrapment temperature on the isomeke.

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Ureilitic carbon defects at the nanoscale

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Keywords: ureilites, stacking faults, diaphite nanostructure.

Ureilites, achondritic meteorites composed predominantly of ultramafic silicate minerals (olivine and pigeonite) with minor carbon phases (graphite and diamond) and Fe-Ni alloys, are hypothesized to originate from a common parent body, the Ureilitic Parent Body (UPB) (Goodrich, 1992). Catastrophic impact events likely disrupted the UPB, which is estimated to have had a maximum diameter of 180–200 km based on mafic silicate analyses and potential daughter body investigations. Ureilites exhibit varying shock levels (classified S1–S7 via optical silicate features), making them ideal for studying shock-related carbon phase evolution (Stöffler et al., 2018).

A central scientific debate concerns the formation mechanism of carbon phases in ureilites. Three hypotheses are proposed: i) chemical vapour deposition, ii) static high-pressure/high-temperature conditions, and iii) shock-induced processes. Current evidence strongly supports shock impact events as the primary formation mechanism for diamonds (Nestola et al., 2020; Barbaro et al., 2023). This study addresses this debate through nanoscale transmission electron microscopy (TEM) analysis of shock-induced defects in ureilites across shock stages (S2–S6) (Stöffler et al., 2018). By characterising defects in graphite and diamond, we aim to correlate shock levels with microstructural deformations, refine shock pressure-temperature constraints, and validate the shock origin hypothesis for diamond formation.

Five ureilitic meteorites from Frontier Mountain, Antarctica (FRO 95028 [S2], FRO 01089 [S3], FRO 97013 [S3/S4], FRO 01088 [S5], FRO 01012 [S6]) were analyzed. Carbon aggregates were manually extracted from shocked regions. Focused ion beam (FIB) lamellae, prepared using a TESCAN-SOLARIS SEM/FIB system (University of Padova), were examined via TEM (Talos F200-X G2 S/TEM, 200 kV) at the Schwiete Cosmochemistry Laboratory, Goethe University, Frankfurt.

Different key shock-related features emerged in diamond and graphite crystals. The TEM findings align with prior micro-XRD and micro-Raman spectroscopy (MRS) data (Barbaro et al., 2023), reinforcing shock-stage correlations. The systematic defect progression confirms that impact-driven shock metamorphism best explains diamond genesis in ureilites, resolving a longstanding controversy about carbon in ureilites.

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Molecular dynamics study of high-pressure melting of CaO: simple structure, complex behavior

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Keywords: melting, molecular dynamics, overheating ratio.

Calcium oxide (or lime, its name as a mineral with B1 *fcc* structure) is a key component in various scientific fields and technical applications (e.g. metallurgical slags, refractory and building materials, CO_2 capture and sequestration). Quantitative data on its thermodynamics and melting behavior form the basis for understanding its reactions and phase relations in multicomponent systems. The thermodynamic properties of liquid CaO were never determined experimentally due to a very high melting point and the resulting high vapor pressure. The only available experimental information is the melting point (T_f). However, even this characteristic temperature is still a matter of debate as the available values in the literature vary from 2843 to 3223 K, with a discrepancy of almost 400 K in the experimental measurements. The high reactivity of CaO with respect to water and CO_2 is believed to be one of the main reasons why the melting point of this material is so sensitive to the experimental conditions and setup, which makes T_f values highly uncertain. In addition to that, some experiments performed by the use of tungsten crucibles could lead to the underestimation of the melting temperature due to the eutectic reaction of lime and the tungsten crucible. Finally, performing experiments in oxidizing or reducing environments could determine variations in the observed melting point up to 30−50 K.

In this study, a detailed theoretical investigation of CaO in the solid and liquid state is performed by means of molecular dynamics (MD) simulations, including both classical and *ab initio* approaches. We calculate the melting temperature of CaO by two different techniques (i.e. the void-nucleated melting and the two-phase coexistence method), aiming to resolve discrepancies in experimental data on the melting point (Menescardi et al., 2024). The obtained results are $T_f = 3066 \pm 12$ K and $T_f = 2940 \pm 65$ K using the former and the latter method, respectively. MD results are thus in general agreement with the higher experimental values, obtained in crucible-free environments either by the use of solar furnaces or by laser heating on levitated samples. Additionally, we calculate the enthalpy of fusion ($\Delta H_f = 80.37$ kJ/mol) and, for the first time, the high-pressure melting curve of lime without making any assumption on the Clapeyron slope. By comparing the calculated melting temperature (T_f) with the thermal instability limit corresponding to the homogeneous melting temperature of the solid (T_s), it turns out that T_s increases more steeply than T_f with increasing pressure. Therefore, the assumption of a constant overheating ratio (i.e. $\eta = T_s/T_f - 1$) commonly made in MD melting simulations is not of general validity. MD results obtained on CaO in this study show that the overheating ratio sensibly depends upon pressure, increasing from 19% to 30% in the pressure range from 0 to 30 GPa. These findings thus contribute to better constrain the CaO phase diagram at planetary conditions.

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Relationship between the crystal chemistry of mantle minerals and their elastic properties

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Keywords: elasticity, crystal chemistry, Earth's mantle.

During my PhD research, conducted under the supervision of Prof. Chiara Domeneghetti, I became fascinated by the close interconnection between a mineral atomic structure and its physical properties. Since then, one of my scientific interest has been to decipher how minor variations in the crystal chemistry of minerals affect their macroscopic response to external conditions such as temperature and pressure. Element substitutions in rock-forming minerals govern a variety of processes occurring on the surface and interior of the Earth from the transport of volatiles into the deep mantle to heat transfer mechanisms, and from oceanic crust subduction to the generation of seismic heterogeneities, just to name a few. The crystal chemistry of minerals, thus, represents a fundamental key to understanding such processes. In the particular case of seismic heterogeneities, for instance, studying the effect of cations substitution on the acoustic wave velocities of mantle minerals can help address open questions regarding the thermal or compositional origin of these heterogeneities. Three case studies will be presented here, in order to elucidate the ongoing significance and innovation in high-pressure, high-temperature crystal-chemical investigations. The effect of Fe and Al substitution on the elastic behaviour of majoritic garnets and bridgmanite will be discussed. Additionally, the relationship between the complex chemistry of calcium ferrite-type structures, which are likely the major hosts of Na and Al in the Earth's lower mantle, and their elastic properties also will be presented.

Thermoelastic behavior and temperature induced structural evolution of grossite; experimental and *ab-initio* calculation data

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Keywords: grossite, negative thermal expansion, high-temperature crystal structure.

The thermal expansion of grossite ($CaAl_4O_7$) has been investigated by single crystal X-ray diffraction at the XRD1 beamline in Elettra, using a Cryostat and a gas blower, in the 100-1080 K temperature range, collecting every 20 K. A 100 K *T*-range of overlap was collected to scale low-*T* cryostat data collections with high-*T* gas blower data collections. This resulted in 55 datasets from which full structure refinement was obtained. No change in symmetry was observed in the whole *T*-range. Instead, a negative thermal expansion has been observed for the *c*-lattice parameter up to 400 K. At $T > 400$ K, this lattice parameter increases with a rate that increases with temperature. Overall, the change is within 0.012 Å. A change of 1.2% in volume is observed in the whole *T*-range. These results agree with the previous experimental evidence of very limited thermal expansion ($\alpha_V = 4.1\times10^{-6}$/K at 1173 K), following Jonas et al. (1998) and Fukuda & Yamauchi (2002), with had much more limited and low precision data. We have also observed negative volume thermal expansion, but only at $T < 160$K, a temperature value coincident with the start of *b*-lattice expansion. Therefore, it appears that the *c*-lattice contraction is responsible for the observed cell-volume contraction below 160 K. A Detailed study of bond geometries and bond-valence variations extracted from the structure refinement sheds light on this particular behaviour.

The thermal expansion was also studied by *ab-initio* calculations using density functional theory and the quasiharmonic approximation (DFT-QHA) and WC1LYP functional. The data obtained for the phonons volume dependence yields α_V that is negative < 130K and a very low value ($\alpha_{V,300} = 6.31\times10^{-6}$/K) in agreement with experimental data.

Jonas S. et al. (1998) - A new non-silicate refractory of low thermal expansion. Ceram. Int., 24(3), 211-216, https://doi.org/10.1016/S0272-8842(97)00004-7.

Fukuda K. & Yamauchi K. (2002) - Anisotropic thermal expansion in $CaAl_4O_7$. J. Mater. Res., 17(5) 1050-1054, https://doi.org/10.1557/JMR.2002.0155.

Coesite under non-ambient conditions via in situ Raman spectroscopy and first principles calculations

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Keywords: coesite, Raman spectroscopy, HF-DFT.

Despite the significance of coesite in mineralogy and petrology, only few experimental studies have been devoted to the evolution of its Raman scattering signal under non-ambient conditions, which in turn provides important information about its atomic dynamics. Most of the previous studies have focused on the coesite behaviour at very-high pressure (P) only (e.g. Hemley, 1987; Černok et al., 2014), whereas the coesite behaviour at high temperature (T) remains poorly documented (Gillet et al, 1990; Liu et al, 1997). In this study, natural coesite crystals from the Dora-Maira massif (Western Alps, Italy) were investigated up to 9 GPa at ~293 K and between ~80-1400 K at ~0.0001 GPa. Hard-mode Raman spectroscopy at high pressure shows anomalous behaviour of several Raman peaks above ~6 GPa, which may be linked to small structural re-arrangements occurring in coesite when approaching the stishovite thermodynamic stability field. This anomalous trend observed for the Raman-active modes is confirmed also by *ab initio* HF-DFT calculations performed at the WC1LYP level of theory in the pressure range from 0 GPa to ~12.3 GPa. On the other hand, coesite Raman peaks upon heating show strong non-linear behaviour with temperature of both the wavenumber (w) and *full-width-at-half-maximum* (FWHM). The resulting trends in w(T) appear different compared to the previously published data. Most likely, this is due to the much larger number of collected spectra within the same temperature range in our experiment as well as to the improved capabilities of modern spectrometers and heating stages. It will be also discussed to which extent differences in the experimental set-up and temperature ramps may affect the estimates of the mode Grüneisen parameter and other phonon-related solid-state properties.

Černok A. et al. (2014) - Pressure-induced phase transitions in coesite. Am. Mineral., 99, 755-763, http://doi.org/10.2138/am.2014.4585.

Gillet P. et al. (1990) - High-temperature Raman spectroscopy of SiO_2 and GeO_2 Polymorphs: Anharmonicity and thermodynamic properties at high-temperatures. J. Geophys. Res., Solid Earth, *95*, 21635-21655, https://doi.org/10.1029/jb095ib13p21635.

Hemley R. J. (1987) - Pressure dependence of Raman spectra of SiO_2 polymorphs: α-quartz, coesite, and stishovite. High-Pressure Research in Mineral Physics: A Volume in Honor of Syun-iti Akimoto, 39, 347-359, https://doi.org/10.1029/gm039p0347.

Liu L. et al. (1997) - Raman spectra of high-pressure polymorphs of SiO2 at various temperatures. Phys. Chem. Minerals, 24, 396-402, https://doi.org/10.1007/s002690050053.

Strain and elasticity as critical determinants of trace element partitioning, solid solution formation and phase transitions

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Keywords: strain, elasticity, phase transitions.

Replacing one cation by another with different size in silicate and oxide structures creates a local strain field and, hence, involves a change in elastic energy. This combination underpins the systematic manner in which partitioning of trace elements between crystals and liquid depends on the size of the cation involved and the elastic properties of the crystal. The diameter of such strain fields also constrains the amount of substitution which can occur in a solid solution before the temperature at which a displacive transition starts to deviate from that of the pure phase – the plateau effect. At the point where the local strain fields around individual substituted cations start to overlap, local strain heterogeneity in the crystal is on a length scale of ~10's to ~100's of angstroms, and can be characterised by measurements of line broadening in infrared spectra. The elastic energy associated with the local strain effects can account for thermodynamic properties of the phenomenologically rich phase systems jadeite-omphacite-augite and plagioclase feldspar. As shown clearly by Al/Si ordering in synthetic anorthite, for example, the reduction in local strain heterogeneity accompanying Al/Si ordering scales with the enthalpy change. Lattice distortions also play a fundamental role in determining the underlying physics of phase transitions since critical fluctuations are suppressed by the long interaction lengths of strain fields. For example, WO_3 has a series of phases, most of which are ferroelastic, with transitions that conform to the expectations of Landau theory. The sequence with falling temperature is *Pm*-3*m* - *P*4/*nmm* - *P*4/*ncc* - $P2_1/c$ - *Pbcn* - $P2_1/n$ - *P*-1 - $P2_1/c$. Each transition is accompanied by characteristic changes in spontaneous strains, elastic properties and acoustic loss.

Structural complexity of humboldtine ($FeC_2O_4 \cdot 2H_2O$) at high pressures

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Keywords: carbon cycle, extreme conditions, synchrotron.

Humboldtine ($FeC_2O_4 \cdot 2H_2O$) is an exceptionally rare organic mineral, remarkable for being one of the very few naturally occurring metal-organic compounds in the Earth's crust. It recently drew international attention after the rediscovery of a long-forgotten specimen in a German museum, effectively doubling the number of known occurrences and highlighting its extreme rarity (Bressan, 2024). Despite its limited natural presence, humboldtine holds considerable scientific interest owing to its dual inorganic-organic character, reflecting the intertwined geochemical processes where biogenic organic acids and inorganic iron phases interact in water-rich, reducing environments.

Its synthetic analogue, iron(II) oxalate dihydrate, has been widely used as a precursor in mineral physics research (Cerantola et al., 2015), and has been extensively studied in materials science, catalysis, and battery research for its distinctive solid-state properties. However, despite considerable investigations have been performed on this compound at ambient conditions, its structural behavior under extreme pressures and temperatures remains largely unexplored. In this context, humboldtine's unique composition makes it an ideal model compound for probing the deep Earth's water and carbon cycles. Mapping its stability, structural transitions, and decomposition pathways under extreme conditions provides critical insight into the behavior of carbon- and water-bearing phases in the Earth's interior.

In this study, we investigate the response of humboldtine to compression using synchrotron-based X-ray diffraction, Mössbauer spectroscopy, and X-ray emission spectroscopy. We identify a series of pressure-induced structural transitions, dominated by two key transformations: (i) a change in iron coordination from sixfold to eightfold above ~20 GPa, and (ii) the formation of high-pressure oxalate $(C_2O_5)^{4-}$ units above 40 GPa, marked by a transition in carbon hybridization from sp^2 to sp^3. These findings shed light on the potential stability of oxy-carbon species in the deep Earth and contribute to our understanding of carbon speciation and cycling under extreme conditions.

Bressan D. (2024) - https://www.forbes.com/sites/davidbressan/2024/01/19/one-of-the-rarest-minerals-on-earth-found-thanks-to-a-75-year-old-letter/.

Cerantola V. et al. (2015) - High-pressure spectroscopic study of siderite ($FeCO_3$) with a focus on spin crossover. Am. Mineral., 100, 2670-2681, https://doi.org/10.2138/am-2015-5319.

Crystal-chemistry and thermo-elastic behavior of chlorite: implications for shear accommodation in subduction zones

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Keywords: chlorite, polytypism, PVT EoS.

Chlorite is one of the most important water-bearing phases and its behavior at high pressure conditions has a significant role in the modeling of dehydration processes in subduction zones (Poli & Schmidt, 2002; Fumagalli et al., 2014). A previous study on single crystals of natural clinochlore (Val d'Ala, Italy) allowed the determination of its bulk modulus both at room temperature and 600 K (Chrappan Soldavini et al., 2024). Combining with the previous data a synchrotron single crystal X-ray diffraction (SC-XRD) study from 100 K to 930 K performed at room pressure on the same sample, we report the first single-crystal PVT equation of state for clinochlore up to 4.5 GPa. As reported in Chrappan Soldavini et al. (2024), the high pressure (HP) behavior of clinochlore is characterized by two phase transitions, the latter involving a significant volume discontinuity with a volume reduction of 0.7% and a significant effect also on the bulk modulus. This phase transition has been associated to a polytypic phase transition with the stabilization of a chlorite polytype that was predicted theoretically by Brown & Bailey (1962) but never observed before. Despite this polytypic phase transition having been observed at pressure around 8.5 GPa, incompatible with the stability field of clinochlore in multiphase systems, its negative slope boundary in the pressure-temperature space suggests that this could indeed be an important structural variation under higher temperature (HT) conditions, compatible with subduction zones. We report two experiments conducted using the large-volume press combined with synchrotron powder XRD (ID06-LVP, ESRF) starting from the same clinochlore sample and resembling subduction P-T paths. Interestingly, we observed the same phase transition in both experiments. We also performed a SC-XRD compressibility study on a ripidolite sample and observed the same phase transition at around 8.5 GPa, suggesting that the composition of chlorite does not play an important role on its behavior upon compression. Additionally, we report in-situ powder diffraction experiments on natural chlorites with different iron and/or chromium content to assess the crystal-chemical effect on the thermal expansion coefficient of this phase. Our results offer valuable insights on the crystal-chemical and thermo-elastic features of chlorite unveiling the role of polytypic phase transitions in subduction contexts. We suggest that this phase transition, which is related to a relative shifting of the talc-like layers that form the crystal structure, could accommodate shear stresses preventing chlorite from early destabilization. A widening of the chlorite stability field could then have an interesting impact on the water storage and transport to the mantle.

Brown B.T. & Bailey S.W. (1962) - Chlorite polytypism: I. Regular and semi-random one-layer structures. Am. Mineral., 47, 819-850.

Chrappan Soldavini B. et al. (2024) - High-pressure phase transition in clinochlore: II*a* polytype stabilization. Am. Mineral., 109, 1834-1838, https://doi.org/10.2138/am-2023-9277.

Fumagalli P. et al. (2014) - The high-pressure stability of chlorite and other hydrates in subduction melanges: experiments in the system Cr_2O_3–MgO–Al_2O_3–SiO_2–H_2O. Contrib. Mineral. Petrol., 167, 1-16, https://doi.org/10.1007/s00410-014-0979-5.

Poli S. & Schmidt M. (2002) - Petrology of subducted slabs. Ann. Rev. Earth Planet. Sci., 30, 207-235, https://doi.org/10.1146/annurev.earth.30.091201.140550.

High-pressure and phase transitions in dalyite, a Zr-silicate

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Keywords: Zr-phases, phase-transition, HP synchrotron diffraction.

Dalyite, ideally $K_2ZrSi_6O_{15}$, is a rare potassium zirconium silicate found as accessory phase in peralkaline granites and syenites, late-stage pegmatites, charoitites, lamproites, lamprophyres, fenites and carbonatites. Dalyite is known to provide useful insights on the geochemical composition of magmatic systems, since it is the stable Zr phase after zircon at high K_2O content and low Na_2O activity. Currently, the relationship among the Zr-bearing phases and their phase stability are still poorly constrained.

A natural single-crystal of dalyite with composition $(K_{1.74(8)}Na_{0.14(1)})(Zr_{0.92(3)}Ti_{0.01(1)})Si_{6.09(4)}O_{15}$ was recovered from the alkaline syenite of Agua de Pau (Sao Miguel, Azores), known to present a peculiar mineralogy (Nazzareni et al., 2019).

Dalyite symmetry is S.G. *P*-1, a = 7.37 Å, b = 7.73 Å, c = 6.91 Å, α = 106.2°, β = 111.5°, γ = 100.0°. Its structural evolution and compressibility were studied by *in-situ* single-crystal synchrotron X-ray diffraction up to 20.52(5) GPa. In the *P*-range investigated we observed: (*i*) a second order (distorsive) phase transition, from dalyite to dalyite-II (S.G. *P*-1), between 9.90(5) and 10.68(5) GPa, and (*ii*) a first-order phase transition, from dalyite-II to dalyite-III (S.G. *P*-1), between 11.06(5) and 12.03(5) GPa. Fitting the *PV* data with a second-order Birch–Murnaghan EoS (BM2) we obtained a value of K_{V0} = 51.4(4) GPa for dalyite (V_0 = 332.5(2)Å^3) and K_{V0} = 39(1) GPa for dalyite-III (V_0 = 670(4)Å^3); due to the narrow stability field of the dalyite-II polymorph (Å1.3 GPa) its elastic parameters could not be determined. The structure accommodates the deformation induced by pressure by increasing anisotropy, from dalyite having a strain ellipsoid axial value of ε_1:ε_2:ε_3~1.69:1.28:1 (calculated between 0.22(5) and 9.90(5) GPa) to dalyite-III with ε_1:ε_2:ε_3~6.4:2.0:1 (calculated between 12.03(5) and 20.52(5) GPa). Both phase transitions have been found perfectly reversible in character and the high-pressure polymorph structures have been solved. From dalyite to dalyite-II and dalyite-III the unit-cell doubled and the coordination of K polyhedra increases from eight-to nine-fold. Interestingly, before the first phase transition the SiO_4 tetrahedra have a significant role in accommodating the bulk compression and show different bulk compressibility (= 47(4) GPa, = 74(14) GPa and = 108(20) GPa), but after the transition the compressibility is accommodated mainly by deforming the ZrO_6 octahedra, the β-wollastonite chains and the 4- and 6-mRs tetrahedra rings The deformation of the SiO_4 tetrahedrons and Zr-polyhedrons constitutes a rather peculiar and unusual behaviour, rarely observed before in high-pressure studies.

Despite its rarity, dalyite records peculiar geochemical processes in peralkaline systems and the definition of the structure stability and single site elasticity constitute a novel valuable information for a better understanding of Zr partitioning in different classes of structures.

Nazzareni S. et al. (2019) - Discovery of moissanite in a peralkaline syenite from the Azores Islands. Lithos, 324, 68-73, https://doi.org/10.1016/j.lithos.2018.10.036.

Lead and Sr-feldspar revisited: new room and high pressure Raman data

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Keywords: Pb and Sr feldspars, Raman spectroscopy, high pressure.

Lead ($PbAl_2Si_2O_8$) and strontium ($SrAl_2Si_2O_8$) feldspars are synthetic analogues of the rock forming feldspars. They share the same Al/Si 1:1 ratio as anorthite, but are monoclinic, with space group *C*2/*m* in Al/Si disordered and *I*2/*c* in ordered configurations.

These phases were extensively studied in the '90s as models for the structure of feldspars with changing pressure, temperature and compositions. More recently renewed interest stems for their potential as environmental traps for toxic elements, as high-performance ceramics, and, for Sr-feldspar, as a host for rare earth elements, which promote important luminescence phenomena.

Recent and less recent studies however lack in the analysis of the vibrational features of Pb and Sr feldspars. Among spectroscopic methods, micro-Raman provides a non-destructive and simple way to identify the examined phases, to highlight short-range order and to point the vibrational features of the transformations that occur in feldspars. In view of the existing well-characterized collection of samples from earlier synthesis, we started an investigation collecting Raman spectra of Sr and Pb feldspars at room and high pressure.

Preliminary results are:

- Ca-Sr feldspars: Raman signatures of the phase transitions at room temperature between *P*-1, *I*-1 and *I*2/*c* structures were found. The transition to the *I*-1 structure occurs at Sr content higher than 0.6 apfu. It occurs with clear Raman evidence, whereas it can hardly detected by electron and XRD diffraction. We suggest that the higher mechano-luminescence observed for compositions in the *P*-1 range close to the transition is related to short range ordered *P*-1 domains, which can easily switch to a *I*-1 structure by mild compression (Curetti et al., 2024).
- Order and disordered Sr and Pb feldspars: room temperature oriented Raman spectra of ordered and disordered Sr and Pb feldspars were collected on (010) at the optical extinction conditions. The spectra in Pb-feldspar show a strong orientational effect, and a major difference between ordered and disordered configurations. In Sr-feldspar instead orientation and Al-Si disorder show lesser effects. Moreover, ordered and disordered Pb-feldspar peak positions shows with other Al/Si 1:1 Ca, Sr, Pb and Ba feldspars, trends which are in turn dictated by ionic radius, mass, or none of the two, with differences between ordered and disordered Pb feldspars. The point was related to the so called lone pair effect, of non bonding $6s^2$ electrons in Pb, which cause a distortion in the coordination sphere.
- High pressure on lead feldspar: an in situ Raman high pressure run, up to 10 GPa, was done on a lead feldspar crystal previously investigated by HP-SCXRD investigation (Curetti et al., 2015). The evidence for the phase transition to $P2_1/c$ at P higher than 7 GPa was confirmed, but even stronger Raman evidence was observed of the rearrangement in Pb-O bond distances due to softening in the *I*2/*c* field, preliminary to the transition, between 5.8 and 6.3 GPa.

Curetti N. et al. (2015) - High-pressure equation of state and phase transition in $PbAl_2Si_2O_8$ feldspar. Am. Mineral., 100(7), 1568-1577.

Curetti N. et al. (2024) - Raman spectroscopy, phase transitions, microstructures, and mechano-luminescence in Ca-Sr feldspars ($CaAl_2Si_2O_8$-$SrAl_2Si_2O_8$), J. Raman Spectr., 55, 833-848.

The pressure-induced stiffening of quartz and its effect on the strain-stress relationship. Implications for elastic geobarometry

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Keywords: elastic geobarometry, quartz-in-garnet, elasticity.

Elastic geothermobarometry, a method in metamorphic petrology for retrieving the pressure and temperature conditions of inclusion entrapment, has undergone significant development since its theoretical origins described by Rosenfeld & Chase (1961), with widespread applications in mantle and metamorphic petrology (Kohn et al., 2023, and references therein). Consider a scenario with a softer inclusion inside a stiffer host (e.g., quartz in garnet). During entrapment, both the inclusion and host are in elastic equilibrium with the external pressure. Decompression and cooling lead to strain and pressurization of the inclusion, measurable directly through X-Ray diffraction or indirectly through Raman spectroscopy.

Two primary methods are commonly employed to calculate inclusion pressures. The first method assumes hydrostatic stress, converting volume strain into pressure using the equation of state. However, recent studies indicate that quartz inclusions are seldom under hydrostatic stress, and strong differential strains can lead to significant errors (Gilio et al., 2021). The second method utilizes the elastic tensor (C_{ij}) for the inclusion to convert strain into stress: $s_i = C_{ij}\, e_j$. A phase subjected to a certain pressure normally becomes stiffer ($\partial C_{ij} / \partial P > 0$). In elastic geothermobarometry the inclusion pressures are low and so this stiffening is generally assumed to be negligible. Inclusion stress is therefore calculated with the elastic tensor values measured at room pressure and ambient temperature.

We will discuss the validity of assuming $\partial C_{ij} / \partial P = 0$ in quartz and other minerals commonly used in geothermobarometry (zircon, olivine, and rutile) and we will describe a method to account for C_{ij} stiffening when calculating inclusion pressures to show the implications in elastic geobarometry.

Gilio M. et al. (2021) - Elastic geobarometry: how to work with residual inclusion strains and pressures. Am. Mineral., 106, 1530-1533, https://doi.org/10.2138/am-2021-7928.

Kohn M.J. et al. (2023) - Elastic thermobarometry. Ann. Rev. Earth Planet. Sci., 51, 331-366, https://doi.org/10.1146/annurev-earth-031621-112720.

Rosenfeld J.L. & Chase A.B. (1961) - Pressure and temperature of crystallization from elastic effects around solid inclusions in minerals? Am. J. Sci., 259, 519-541, https://doi.org/10.2475/ajs.259.7.519.

Determination of Al/Si Ordering in K-feldspars: comparison of methods

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Keywords: Al/Si ordering, method-comparison, Raman.

The chemical and structural characterization of feldspar group minerals provides valuable insight into their geological environments, particularly with respect with pressure and, especially, temperature. Considering, in particular, the K-feldspar polymorphs, one of the most commonly used proxies for inferring petrological information is the determination of the degree of (Al/Si) ordering within the four ideally non-equivalent tetrahedra of the structure (T_{1o} -T_{1m} -T_{2o} -T_{2m}).

We present a comparison of the most widely employed analytical techniques for evaluating K-feldspar ordering, including X-ray diffraction (XRD; Kroll & Ribbe, 1987) on both powders and single-crystals, Fourier-transform infrared spectroscopy (FTIR; Ma, 1988), optical crystallography (Su et al., 1984), along with the novel application of Raman spectroscopy. We discuss and compare the results obtained from these methods as applied to selected samples from the Sabatini Volcanic Complex (SVC) in central Italy, highlighting the advantages and disadvantages of each technique. In particular, while XRD methods and especially the structural refinements have been highly valued for providing the most direct and reliable measurements of (Al,Si) partitioning, spectroscopic methods have distinguished themselves through their practical applicability and rapid analytical performance.

Finally, we emphasize the practical relevance of the petrological information derived from K-feldspar ordering in the SVC volcanic products, as previously highlighted by Della Ventura et al. (1992). Specifically, the degree of ordering evaluated in K-feldspar from the volcanic ejecta can serve not only as a reliable indicator of thermal history but, with proper calibration, also as a proxy for the depth of the volcanic intrusion from which the ejecta originated.

Della Ventura G. et al. (1992) - Composition and structural state of alkali feldspars from ejecta in the Roman potassic province, Italy; petrological implications. Eur. J. Mineral., 4, 411-424, http://doi.org/10.1127/ejm/4/3/0411.

Kroll H. & Ribbe P.H. (1987) - Determining (Al,Si) distribution and strain in alkali feldspars using lattice parameters and diffraction-peak positions; a review. Am. Mineral., 72, 491-506.

Ma H. (1988) - Comparison of K-feldspar ordering by X-ray powder and infrared spectroscopy and its relations to Al occupancy and equilibrium temperature. Acta Mineral. Sinica, 143-150.

Su S. et al. (1984) - Optic axial angle, a precise measure of Al, Si ordering in the T1 tetrahedral sites of K-rich alkali feldspars. Am. Mineral., 69, 440-448.

On the incorporation of the larger alkali ions (Rb,Cs) into tobermorite related phases

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Keywords: tobermorite, caesium, rubidium.

The tobermorite supergroup of minerals comprises calcium silicates hydrates, which are based on *dreier* double chains of [SiO_4]-tetrahedra, thus belonging to the group of band silicates (Biagioni et al., 2015). While the various members of this family represent rather exotic species within the mineral kingdom, their synthetic counterparts are of great importance for applied mineralogy because of their close relationship with the so-called C-S-H phases, representing the major binding compounds in concrete (Taylor, 1997). Furthermore, they have been the focus of research as cation exchangers and for their potential applications in waste disposal.

Despite the fact that the crystal chemistry of the tobermorite phases has been investigated in detail, there is a lack of information regarding the incorporation of larger monovalent cations, such as Rb or Cs, into the tunnel-like cavities of the structures. In the course of an ongoing research project, synthesis runs under different experimental conditions were performed to fill this gap in crystallochemical knowledge. To date, we have successfully grown single crystals of the following two compounds: $Cs_2Ca_4[Si_6O_{17}]$ (dry, phase I) and $Rb_{1.7}1Ca_4[Si_6O_{15}(O,OH,H_2O)_4]$ (hydrothermal, phase II). The crystals were of sufficient size to be studied using laboratory (I) or synchrotron (II) X-ray diffraction. The basic crystallographic data are as follows: phase I: space group $P2_1/n$, a = 11.1053(7), b = 7.3138(4), c = 22.2609(15) Å, β = 98.289(6)°, V = 1789.2(2) Å^3 and phase II: space group $P2_1/m$, a = 6.7766(4), b = 22.3162(10), c = 6.7782(4) Å, β = 114.056(7)°, V = 936.02(8) Å^3.

The compounds demonstrate structural similarities with clinotobermorite (I) and paratobermorite (II). Even though the silicate chains differ considerably with respect to their conformation and their degree of corrugation, the tunnels within the network formed by the silicate chains, as well as the layers containing CaX_7 and CaO_6 (X: O,(OH),H_2O) polyhedra, are devoid of water molecules. While the Cs-ions are located on two well-defined positions, the distribution of the Rb-cations shows a high degree of disorder involving a total of four sites which are only partially occupied. Structural studies have been complemented by an analysis of the previously unknown compounds based on concepts of OD-theory.

The results of this study may be useful for understanding the high cesium ion selectivity that has been observed for tobermorite-type compounds when tested for the removal and immobilization of Cs (Shrivastava & Komarneni, 1994). In particular, the ^{137}Cs isotope, which emits γ-rays and has a half-life of about 30 years, is highly water-soluble and poses an environmental threat.

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Polymorphic behavior of leucite under high-pressure and high-temperature conditions: insights from synchrotron single-crystal diffraction

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Keywords: leucite, pressure, phase transition.

Leucite, $KAlSi_2O_6$, is a key mineral phase in K-rich mafic to ultramafic volcanic rocks, commonly classified among feldspathoids or zeolites. Due to its widespread occurrence in alkaline magmatic systems, a detailed understanding of its thermodynamic stability, and structural evolution across a range of pressure-temperature (*P*-*T*) conditions, is crucial for interpreting petrological processes at depth. The mineral's physical and chemical properties are intrinsically linked to its crystal structure and the way it responds to changing *P*-*T* conditions.

Leucite displays a well-known sequence of temperature-induced phase transitions: it crystallizes in a high-temperature cubic structure (space group *Ia3d*), but, upon cooling between ~620 and 670 °C, it sequentially transforms into two lower symmetry tetragonal polymorphs ($I4_1/acd$ and subsequently $I4_1/a$), with the latter being the stable ambient form (Hatch et al., 1990). These transformations are accompanied by complex twinning phenomena, which are further influenced by compositional variations and thermal history (Lange et al., 1986; Hatch et al., 1990; Palmer et al., 1997).

Under high pressure and room temperature, previous work has shown that the $I4_1/a$ tetragonal form undergoes a first-order phase transition near 2.4 GPa to a denser, metrically triclinic polymorph, tentatively indexed in the *P*-1 space group (Gatta et al., 2008). In our study, we re-examined this high-pressure behavior and, for the first time, extended the investigation to simultaneous high-pressure and high-temperature conditions, using *in situ* single-crystal synchrotron X-ray diffraction at the beamlines P02.2 (PETRA III) and ID15B (ESRF).

Our experiments reveal a previously unreported polymorphic transition of leucite from the ambient tetragonal $I4_1/a$ structure to a trigonal polymorph (space group *R*-3) at pressures exceeding 2.2–2.5 GPa. Remarkably, this transition occurs both at room temperature and under heating, suggesting that compression kinetics may play a key role in stabilizing this new structural form. These findings underscore the complex polymorphism of leucite and highlight the need for accurate structural characterization to fully understand its stability fields under deep Earth conditions. Our results open new perspectives for modeling K-rich magmatic systems and their evolution under variable geodynamic settings.

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Columbite-tantalite minerals from Val Vigezzo (VCO province, Piedmont, Italy): a preliminary study

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Keywords: columbite, electron microscopy, microanalysis.

Columbite-group minerals (CGMs) have general formula AB_2O_6 (usually A = Fe^{2+}, Mn^{2+} and B = Nb^{5+}, Ta^{5+}) and are well-spread in pegmatitic settings. This group of minerals has petrogenetic significance, as their texture reflects variations occurred in the crystallization environment, i.e. during the magmatic and hydrothermal evolution of granitic/pegmatitic systems (e.g. Sarbajna et al., 2000) and are important from a crystallographical point of view as well. CGMs are found with ordered cation distributions, where the A site is exclusively occupied by Fe and Mn and the B site by Nb and Ta, as well as with disordered distributions, where no distinction between the A and B site is present and the structure is ascribable to that of ixiolite (e.g. Chukanov et al., 2023). Here, we report a preliminary study by means of scanning electron microscopy (SEM) and transmission electron microscopy (TEM), both coupled with an energy dispersive x-ray spectroscopy (EDS) system, of a set of four crystals from the tertiary alpine pegmatites of Val Vigezzo (Verbania-Cusio-Ossola province, Piedmont, Italy): Piano dei Lavonchi (PLV1), Pizzo Marcio Nord (PMN2 and PMN6-2) and Rio Vasca (RVS). The crystals are found within different types of rocks, such as unaltered quartz-feldspar pegmatites, as well as heavily-altered, completely-albitized units. In BSE images, CGMs are characterized by different types of compositional zoning, namely patchy and growth zoning. Sample PLV1 has a growth zoning, with a columbite-(Fe) composition for both the core and the rim; PMN2 is an inversely-zoned crystal, with a tantalite-(Mn) core, a borderline columbite-tantalite-(Fe) intermediate rim and a columbite-(Fe) external rim; PMN6-2 is a normally-zoned columbite-(Mn) crystal, with a rim richer in Mn than the core; RVS is a patchy-zoned crystal, with tantalite-(Fe) portions mixed up with columbite-(Fe) portions. At the TEM scale, the studied thin region has a columbite-(Fe) composition in the case of PLV1; tantalite-(Fe) composition for PMN2; columbite-(Fe) for PMN6-2; tantalite-(Fe) composition for RVS. The results indicate a great variability in the crystallization conditions during pegmatitic cooling. Unit cell parameters, obtained from calibrated electron diffraction patterns (Capitani et al., 2006), taken along zone axis are: a = 14.373(5), b = 5.754(2), c = 5.067(2) Å for PLV1, a = 14.353(4), b = 5.627(2), c = 5.076(2) Å for PMN2, a = 14.401(6), b = 5.716(2), c = 5.080(2) Å for PMN6-2, a = 14.448(9), b = 5.809(8), c = 5.075(6) Å for RVS. A plot of these parameters in the a-c diagram (Ercit et al., 1995) shows that these columbite crystals fall in the ordered samples region.

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Unusual coordination in novel polyoxometallate-like crystal structures

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Keywords: arsenite, POM, new mineral.

Crystal structures of minerals with predominantly ionic bonding do commonly involve an infinite bonding network, in which cations are surrounded by anions and vice versa, so that charges tend to compensate locally. In crystal chemistry this concept historically evolved from Pauling's rules to more recent bond valence models. Some minerals, arsenites in particular, may considerably deviate from the above principles by the formation of direct bonds between formal cations. This is demonstrated by the examples of octahedral and tetrahedral clusters formed via direct Fe^{2+}-As^{3+} and Cu^{+}-As^{3+} neighbourhoods in the minerals nanlingite and dixenite respectively (Yang et al., 2011; Hawthorne & Hughes, 2021). Deviations from the fully polymerized infinite bonding network may also arise in the polyoxometallates (POM), of which several mineral examples are already known (Krivovichev, 2020). These compounds contain large polyoxoanions, i.e. negatively charged clusters of transition metal oxides. Space between the clusters may be filled by water and charge compensating large cations, rendering these minerals more similar to the molecular crystals known in organic chemistry. The contribution will describe recently discovered arsenite mineral structures which combine the above phenomena, giving rise to unusual coordination environments and unexpected combination of elements.

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Mechanisms of growth of unstrained crystals under stress: implications for mineral equilibria in deforming rocks

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Keywords: molecular dynamics, mineral equilibria, stress.

Understanding the growth and stability of coherently strained crystal layers of identical or differing compositions is fundamental for solving problems ranging from thin-film electronics to the mechanical performance of composite materials. In these applications, it is usually desirable to have coherent interfaces (i.e., perfect lattice correspondence) between the growing film crystal and the crystalline substrate. Studies of epitaxial growth reveal that coherent interfaces are initially favored, but as film thickness increases, stored elastic energy makes strain relief via misfit dislocations energetically preferable, breaking the interfacial coherence. However, high local stresses are required to nucleate these dislocations, and chemo-mechanical surface instabilities of the Asaro–Tiller–Grinfeld (ATG) type have been proposed to generate the necessary stress concentrations (Berréhar et al., 1992). In this contribution we show how the same mechanism can be extended to the growth of new minerals on stressed mineral substrates under lithospheric deformations. From bulk thermodynamic considerations, Gibbs (1876) predicted that the equilibrium between a non-hydrostatically stressed crystal and a fluid containing the same component is unstable. At these conditions a new unstrained crystal must form from the fluid. However, if the existing stressed solid acts as a seed for the crystallization of the new crystalline layer, coherency would impose a large strain on the new phase preventing it to reach a stable equilibrium. Using large–system molecular dynamics (MD) simulations with more than one million particles, we probe the nucleation and growth of a crystalline layer from its pure fluid onto a stressed seed crystal (Mazzucchelli et al., 2024). Our simulations capture dissolution, precipitation, ATG–type surface instabilities, and eventual dislocation formation until a new equilibrium is established. We compute the local Cauchy stress from interatomic forces with one unit–cell spatial resolution, fully accounting for elastic anisotropy. This allows us to resolve stress gradients, concentrations, and discontinuities as the system evolves and deforms providing a direct coupling between the large scale deformation and the local mechanical response. Our results show that new crystalline layers initially grow as strained crystals. ATG instabilities arise spontaneously during layer growth, providing the stress concentrations needed to nucleate misfit dislocations that break coherency and relax the strain of the new crystalline layer. Consequently, new low-stress minerals can grow even while the substrate remains nonhydrostatically stressed, in agreement with the predictions of Gibbs (1876). Our results qualitatively and quantitatively agree with experimental observations in deformed systems (Koehn et al., 2004), and provide new perspetives on predictive quantitative formulations of the coupling of mineral reactions and deformations.

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Transformation mechanism of the isosymmetric high-pressure transition in rhombohedral $K_2Ca_2(CO_3)_3$

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Keywords: potassium double carbonate, high-pressure structure, phase transition.

Rhombohedral $K_2Ca_2(CO_3)_3$ is one of the known subsolidus key phases within the system $CaCO_3$-K_2CO_3 (Shatskiy et al., 2015; Arefiev et al., 2019) with respect to the occurrence of dense potassium carbonates originating from carbonatitic melts and found as mineral inclusions in nature (e.g. Logvinova et al., 2019). Investigations on the structural stability and polymorphic transition associated with the possible pathways along with changes in P,T space include an *in-situ* study under isothermal high-pressure conditions in a diamond-anvil cell. Both Raman spectra and X-ray diffraction pattern obtained from synthetic single-crystal samples clearly indicate a reversible structural phase transition under hydrostatic compression. The transition was found to show a remarkable hysteresis between 2.6 and 4.3 GPa. While the X-ray pattern exhibit the equivalent rhombohedral acentric space-group symmetry *R*3 for both polymorphs, the *c*/*a* ratio is significantly different and reflects the prominent structural changes. High-pressure X-ray crystallography shows that the low-pressure form (Winbo et al., 1997) corresponds to a geometrically frustrated rombohedral lattice with rather high dynamics on individual structural subunits. The isosymmetric high-pressure form, however, corresponds much more to a less disordered proper *R*3 lattice. The change in the positional orientation of the CO_3 groups, which occurs on crossing the critical transition point, was found to be the driving force of the transformation mechanism, thus causing the observed relative changes along the *a*- and *c*-axis directions. The structural changes across the transition were found in turn to be responsible for the destabilisation of the apparently stable rhombohedral high-pressure phase on decompression.

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Experimental insights into the α–β quartz transition at high-pressure and high-temperature

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Keywords: alpha-beta quartz transition, HP-HT experiments.

At pressure and temperature conditions of the lower crust quartz undergoes a displacive phase transition from its trigonal α-phase to a hexagonal β-phase. At room pressure, the α- β quartz transition occurs at 574.1 °C and it is associated with large changes in the thermodynamic and elastic properties. In particular, the bulk modulus drops from approximately 70 GPa to nearly zero over a narrow temperature range of just 10–15 K. While the transition has been extensively studied at ambient pressure, its behaviour under high-pressure and high-temperature (HP-HT) conditions (relevant to Earth's lower crust) remains largely unexplored.

We experimentally investigated the α–β quartz transition under simultaneous HP-HT conditions using synchrotron X-ray diffraction and acoustic velocity measurements at beamline ID06 at ESRF using a multi anvil press up to almost 3 GPa and 1400 °C. From these experiments, we determined values for compressional (Vp) and shear (Vs) wave velocities, as well as the adiabatic bulk modulus (Ks) and shear modulus (G).

Our measurements in the α-quartz stability field align well with existing models (e.g., Abers & Hacker, 2016; Angel et al., 2017), suggesting that elastic barometry using these EoS provides reliable estimates of entrapment pressures for α-quartz inclusions. However, our measured values for Vp and Ks in the β-quartz phase are significantly lower than those predicted by current models (Mingardi et al., 2025). Preliminary in-situ data from laser-heated DAC experiments at ~2 GPa at the Bavarian Geoinstitute for Experimental Geochemistry and Geophysics (BGI) appear to support these results. Given this discrepancy, interpretations of seismic data based on the elastic properties of β-quartz in the lower crust, as well as entrapment condition estimates for quartz inclusions in the β-quartz stability field, should be approached with caution. Furthermore, these results could help to better constrain a new EoS in the HT-HP field of quartz.

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Exploring disorder via X-ray diffuse scattering in cupropearceite, $[Cu_6As_2S_7][Ag_9CuS_4]$, a member of the pearceite-polybasite group

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Keywords: pearceite-polybasite, structural complexity, diffuse scattering.

Minerals of the pearceite–polybasite group, general formula $[M_6T_2X_7][M_{10}X_4]$ with M = Ag and Cu, T = As and Sb, and X =S, Se and Te, have drawn considerable interest due to their physical properties, such as fast ion conduction, and structural complexity (e.g., Bindi et al., 2006). Their structure can be described in terms of two different alternating module layers ($A = [M_6T_2X_7]^{2-}$ and $B = [M_{10}X_4]^{2+}$) stacked along the **c** axis. Three different polytypes have been described: the high-temperature (T) *Tac* polytype, which shows fast-ion conductivity; the partially-ordered *T*2*ac* polytype, and the fully ordered *M*2*a*2*b*2*c* polytype at low T (Bindi et al., 2006). Additional complexity arises from the presence of up to six twin domains, pseudosymmetry, coexistence of different polytypes, and strong diffuse scattering (DS) features. DS in these minerals was studied only by electron diffraction at selected T, i.e. room T, 90 K and 4.2 K (Withers et al. 2008, Bindi et al., 2013). The DS features were interpreted as arising from two substructures: a $[M_6T_2X_7]^{2-}$[$MX_4]^{7-}$ framework substructure and a $[M_9]^{9+}$ substructure, mutually incommensurable with respect to each other (Withers et al., 2008; Welberry & Paściak 2011). Low-T data could not provide a comprehensive answer on the observed aperiodic order, i.e., incommensurate vs. composite modulated structure (Bindi et al., 2013). Moreover, a transformation from the aperiodic structure into a commensurately lock-in phase was observed at 4.2K (Bindi et al., 2013), but due to the lack of data at intermediate T little is known about the evolution of the modulation vector. The occurrence of the lock-in phase was attributed to the ordering of the $X(M)_6$ octahedra in the *A* module, in contrast to the Ag^+ ordering in the conductive *B* module mainly responsible for the stabilization of the various polytypes. X-ray DS data collected at ID28 (ESRF) on a crystal of cupropearceite-*Tac* (from 100 to 325 K) revealed that the DS features in the *hk*0 plane (related to the ordering of Ag^+ in the *B* module) decrease approaching the phase transition toward the ordered polytypes and continue to do so upon cooling, leading to a much weaker signal at 100 K. The diffuse signatures in the *hhl* plane reduce at a slower rate and are still intense at 100 K, suggesting a higher degree of disorder along **c***. Moreover, additional DS features not observed by electron diffraction were detected in the *hh*-4 plane; here, the presence of DS could be related to a precursor state of the lock-in phase, requiring further investigation at low-T. Since the As/Sb ratio could also play a role in this phenomenon, a preliminary characterization of a polybasite-*M*2*a*2*b*2*c* and a polybasite-*T2ac* was performed to separate the contribution of the different structural units to the DS.

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Unravelling the thermal history of rocks using pyroxene intracrystalline geothermometry

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Keywords: pyroxene, intracrystalline geothermometry, closure temperature.

The reconstruction of the thermal history of rocks is of fundamental importance to constrain processes such as magma mixing and lava flow emplacement, to evaluate the risks related to volcanism on Earth and to determine the geological history of other planetary bodies. In conventional petrology cooling rates are often determined by the chemical equilibrium developed between adjacent grains of different mineral phases. However, this process is slow to respond to temperature changes and, therefore all the subsequent dynamic and short duration events experienced by the rock at lower temperatures are not detected by such analyses.

Intracrystalline geothermometry overcomes these problems. Because it is based on cation exchange between two crystallographic sites within a single crystal, it is dominated by much shorter pathways than inter-crystalline diffusion and it thus can record the signature of processes occurred in the order of years and down to a few hundreds of degrees. Over the past 50 years, this method has been firmly established and successfully applied to pigeonite, augite and orthopyroxene-bearing rocks of terrestrial and extraterrestrial origin (e.g., Domeneghetti et al., 2013).

Recently, this method has been used to shed light on the ongoing debate regarding the origin and cooling history of Theo's Flow lava, the terrestrial analogue of Martian nakhlites (Lentz et al., 2011). For this purpose, closure temperatures and cooling rates for six augite crystals of Theo's Flow lava sampled at four different stratigraphic depths have been determined. These results were then coupled with (i) the low viscosity data by Vetere et al. (2019) on the same composition and (ii) the results from finite difference methods to test the possible emplacement mechanisms for Theo's Flow. The combination of geothermometric constraints on augite single crystals and numerical simulations in the framework of a multi-methodological approach, allowed us to demonstrate that Theo's Flow has been formed by multiple magma emplacements that occurred at different times (Murri et al., 2019). Moreover, this discovery also supports the idea that enormous lava flows with similar compositions observed on Mars could be the result of a process where low viscosity lavas were emplaced during multiple eruptions. This has profound implications for understanding the multiscale mechanisms of lava flow emplacement on Earth and other planetary bodies.

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Corundum inclusions in diamonds: a new tool for diamond geobarometry

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Keywords: diamond, inclusions, corundum.

In 1981 the first occurrence of a corundum inclusion associated with a low-Cr_2O_3 garnet within a diamond of unknown origin was reported (Meyer & Gubelin, 1981). The corundum was characterized by 1.30 wt% Cr_2O_3 and assigned to an eclogitic origin. 12 years later, the second finding of corundum in a Type II diamond from São Luiz, Brazil, was reported (Watt et al., 1994), with extremely high Cr_2O_3 reaching over 8 wt%. An eclogitic paragenesis was indicated, and possible evidence of sublithospheric origin was hypothesized to explain the extreme Cr_2O_3 enrichment. Between 2001 and 2004 new discoveries of corundum inclusions in Type II diamonds, from the Juina, Brazil, were reported (Hutchison et al., 2001, 2004), with again extreme enrichment in Cr_2O_3 (above 8 wt%), suggesting a very deep origin for these diamonds within the lower mantle at about 770 km depth. Since 2004, no additional finding of corundum inclusions in diamond has been reported . Based on these four initial publications, we could assume that Cr-rich corundum inclusions indicate a very deep origin.

Here, we identified the first corundum inclusions in four African diamonds (Premier, South Africa). The diamonds did not contain other types of inclusions. Single-crystal X-ray diffraction carried out before and after inclusion release from the diamond showed no residual pressure. The chemical composition of the inclusions indicated very-low Cr content. Although no residual pressure was detected, we attempted, for the first time, to apply elastic geobarometry to the diamond-corundum system to determine the minimum pressure of formation. Surprisingly, our results indicate that even for corundum inclusions characterized by low-Cr content, a minimum depth of 300(±30) km at 1250 °C is necessary to justify the presence of such inclusions in diamond. Therefore, both high- and low-Cr corundum may be of sub-lithospheric origin.

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Celebrating the career of Prof. Chiara Domeneghetti: a legacy of research in mineralogical sciences

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Keywords: Maria Chiara Domeneghetti, mineralogy, teaching.

This session celebrates the outstanding career of Prof. Maria Chiara Domeneghetti, whose more than four decades of contributions have left a profound mark on the fields of mineralogy, crystallography, and planetary sciences. A leading expert in the crystal-chemistry of rock-forming minerals, she has conducted groundbreaking research on cation ordering, phase transitions, and thermoelastic properties of pyroxenes, amphiboles, from terrestrial and extraterrestrial materials. Her innovative work has provided key insights into geothermometry, geospeedometry, and the thermal histories of terrestrial and extraterrestrial rocks.

Furthermore, Prof. Domeneghetti has held pivotal roles in major national and international projects, including EU and Italian Space Agency programs, and was instrumental in advancing research on carbon phases in meteorites and high-pressure mineral inclusions in diamonds. Her academic mentorship shaped numerous PhD and postdoctoral careers, and her teaching at the University of Pavia laid the foundation for generations of geoscientists.

She has also played a pivotal role in academic governance, including leading doctoral programs, participating in national scientific qualification commissions, and directing research units. As a long-standing member of the scientific community and editorial boards, still very active today, Prof. Domeneghetti's legacy continues to inspire excellence in both research and education.

The high-pressure conversion of merrillite to tuite in the upper mantle

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Keywords: phosphate, super-deep diamond, solid-state experiment.

Merrillite [$Ca_9NaMg(PO_4)_7$], which is a common accessory phosphate in meteorites and lunar rocks, was recently identified terrestrially within a super-deep diamond from the lower mantle (Kaminsky & Zedgenizov, 2022). This occurrence suggests formation via retrograde reaction from higher-pressure tuite [γ-$Ca_3(PO_4)_2$]. Both phases are potential reservoirs for rare earth elements (REE) and large-ion lithophile elements (LILE) in Earth's deep interior. Understanding the $Na_3(PO_4)$-$Mg_3(PO_4)_2$-$Ca_3(PO_4)_2$ system's phase relations at upper mantle pressures is crucial to assess merrillite's significance in super-deep diamonds. Prior studies show apatite [$Ca_5(PO_4)_3(Cl,F,OH)$] breakdown at 200-250 km depths to tuite (Pausch et al., 2024), which remains stable to at least 700 km.

To investigate the merrillite-tuite phase boundary, we conducted high-pressure experiments using a multianvil apparatus. Polycrystalline merrillite powder (verified by X-ray diffraction) was synthesized from $CaCO_3$, Na_2CO_3, $(NH4)_2HPO_4$, and $4MgCO_3 \cdot Mg(OH)_2 \cdot 5H_2O$ *via* solid-state reaction. The powder was loaded into Pt capsules, often with $Ca_3(PO_4)_2$, and a pressure marker. Each composition was separated by Re foil. Experiments used an 18/11 assembly with graphite and lanthanum chromite furnaces. Post-experiment analysis involved micro-X-ray diffraction and scanning electron microscopy with energy-dispersive spectroscopy for phase identification.

Initial observations show that merrillite is stable at up to ~5 GPa over a temperature range of 1000-1400 °C. At the same conditions, $Ca_3(PO_4)_2$ tuite is stable. With increasing pressure, merrillite reacts to form Ca-rich tuite coexisting with an Na- and Mg-rich phosphate. At higher pressures (~15 GPa), we observe a single tuite phase containing significant Na and Mg, similar to the initial merrillite composition. This suggests that the NaMgPO4 component plays a role in stabilizing merrillite within the $Ca_3(PO_4)_2$ tuite stability field. Further experiments are needed to refine the pressure of the merrillite-tuite transition and to quantify Na/Mg solubility in both phases.

Kaminsky F.V. & Zedgenizov D.A. (2022) - First find of merrillite, $Ca_3(PO_4)_2$, in a terrestrial environment as an inclusion in lower-mantle diamond. Am. Mineral., 107, 1652-1655, https://doi.org/10.2138/am-2022-8175.

Pausch T. et al. (2024) - The role of calcium phosphates and silicates in the storage and transport of phosphorus at the upper-to-lower mantle transition: An experimental study to 25 GPa in a model peridotitic bulk composition. Geochim. Cosmochim. Acta, 374, 200-216, https://doi.org/10.1016/j.gca.2024.04.026.

Crystal-chemical studies on zirconosilicates from Tamazeght intrusive complex, Morocco

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Keywords: zirconosilicates, Tamazeght, Morocco.

The Eocene Tamazeght complex in Morocco's High Atlas Mountains is a multiphase intrusive body characterized by alkaline to peralkaline compositions. It intruded into Liassic to Cretaceous limestone formations within a Mesozoic graben-like structure, which developed as a result of the Africa–Europe continental collision and the opening of the Atlantic Ocean. Spanning approximately 70 km², the complex comprises a variety of rock types, including silica-undersaturated alkaline to peralkaline rocks, carbonatites, and associated dyke systems (Marks et al., 2008). The literature reports the presence of rare zirconosilicates as accessory minerals within the complex, including catapleiite, elpidite, zircon, and Zr-Ti-Nb-bearing minerals such as eudialyte, hiortdahlite, låvenite, normandite, rinkite, and rosenbuschite. These minerals have been identified through optical studies and electron microprobe analysis only. A detailed chemical screening of the Zr-Ti-Nb phases reveals that they can all be recalculated using the general formula $M_{16}(Si_2O_7)_4(O,OH,F)_8$, where, M represents cations such as Ti^{4+}, Zr^{4+}, and Nb^{5+}, as well as large and low-charge cations like Na^{+} and Ca^{2+}. Notably, this crystal-chemical formula is characteristic of at least three distinct mineral groups: the cuspidine–låvenite group, the rosenbuschite group, and the rinkite group.These mineral groups exhibit a wide range of possible substitutions. In contrast, minerals with different structural arrangements, such as rosenbuschite, hiortdahlite I, and hiortdahlite II, often share similar chemical compositions. This high variability in chemical substitutions and identical crystal-chemical formulas make it challenging to identify phases unambiguously based solely on chemical composition.

Powder XRD is not well-suited for the definitive identification of these minerals, as the diffraction patterns for the strongest reflections are largely overlapping, with only minor variations arising from their modular structural nature. To overcome these limitations, we conducted a combined analytical approach using electron probe microanalysis (EPMA) and single-crystal X-ray diffraction as part of the SYNTHESYS + FR-TAF-Call3-034 project, "The Rare Zirconium-Niobium Silicates of the Alfred Lacroix Collections."

The material analyzed in this study was sampled from specimens collected and described by Jeremine & Dubar (1947) from the Oued Endt locality within the Tamazeght Complex and is currently housed in the collections of the "Muséum National d'Histoire Naturelle" in Paris, France.

A full crystal-chemical characterization was obtained for the zircon-silicates eudialyte *ss*, låvenite and normandite. The crystal structure of eudialyte *ss* was refined up to R_1 = 3.7%. The crystal chemical formula from the structural refinement fits EPMA chemical data, showing a close relationship with samples described in literature. The crystal structure of the wohlerite group minerals lavenite and normandite were refined up to 1.8 and 4.6 % respectively, defining crystal chemical models well-fitting the EPMA data results

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Interconnectivity between crystal chemistry and crystallography in Eudialyte-Group Minerals: A new discovery from the Sierra La Vasca Alkaline Volcanic Complex, Coahuila, Mexico

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Keywords: eudialyte group minerals, fengchengite, Sierra la Vasca alkaline complex

Eudialyte-group minerals (EGMs) are complex Na-Ca zirconosilicates enriched in high field strength elements (HFSEs) and rare earth elements (REEs) and are considered index minerals for agpaitic peralkaline magmatic systems. They are typically characterized by strong enrichment in large ion lithophile elements (LILEs), HFSEs, REEs, halogens, as well as Be, Sn, Zn, and Ga. The eudialyte group comprises over 30 chemically distinct species officially approved by the IMA (Mikhailova et al., 2022). EGMs commonly occur in association with Na-rich silicates such as aegirine and arfvedsonite, and Na-Al silicates including alkali feldspars, nepheline, sodalite, and zeolites, along with various HFSE- and LILE-bearing accessory minerals (Schilling et al., 2011). The Sierra La Vasca alkaline volcanic complex, located in northern Coahuila within the Trans-Pecos Magmatic Province (TPMP), represents a Tertiary magmatic complex comprising two main intrusive bodies of granitic and monzonitic composition, as well as numerous smaller intrusions, including dykes and sills, with compositions ranging from diorite to andesite, dacite, and rhyolite. These bodies intrude a Cretaceous carbonate basement. In this study, we investigate a specific kakortokite-like intrusive body within a marble host rock, with a contact zone represented by a composition of over 90% wollastonite and inclusions of pyrite, minerals of the apatite group and cuspidine. The intrusive lithology is composed of feldspars, pyroxenes, and apophyllite, with accessory phases including calcite, quartz, zircon, and titanite. The HFSE- and REE-rich assemblage is dominated by EGMs, associated with gittinsite, F-Ca-britholite, stillwellite, and kainosite. From a petrogenetic perspective, the intrusion involved the emplacement of a kakortokite-like magma into limestone, resulting in contact metamorphism and the formation of marble, along with the wollastonite-bearing contact zone. Subsequently, all lithological zones were affected by subsolidus metasomatism driven by ascending F- and Ca-rich hydrothermal fluids. Crystallographic analysis shows that EGMs crystallize in the trigonal space group *R*-3*m*, with unit cell parameters a = 14.2426 Å, c = 30.1889 Å, and V = 5303.32 Å^3. Crystal chemical data obtained *via* LA-ICP-MS and normalized on the basis of Si + Zr + Ti + Hf + Nb = 29 atoms per formula unit (apfu), following Johnsen & Grice (1999), yield the following average composition (in apfu): Si 25.7, Zr 2.9, Nb 0.1, Ti 0.3, Fe 2.3, Mn 0.4, Ca 6.0, Na 12.5, K 0.1, La 0.1, Ce 0.2, Nd 0.1, Y 0.1, and Cl 1.9. The integration of crystallographic and chemical data indicates a fengchengite-type composition, characterized by vacancies at the N(5) site. This composition has previously been reported only from the Saima agpaitic complex and its pegmatitic facies in Liaoning Province, NE China (Shen et al., 2017) and provides new and valuable insights into the diversity of eudialyte-group minerals.

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Calculation of elastic moduli and equation of state of dolomite through a Density Functional theory model. A benchmark study of the Hamiltonians

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Keywords: dolomite, theoretical model, elastic properties.

Carbonate minerals are known to be essential in several fields, as regulators of acidity in oceans, transport of nutrients and depuration of contaminants (Rimer et al., 2025). Moreover, it has been thoroughly discussed their major role in the carbon cycle, transporting and recycling it within the deep mantle. In this context, understanding the stability conditions of the carbonates may help to interpret and forecast their dynamics at deep Earth's settings (Reeder, 1983). To this aim, the present study investigated the properties of dolomite, $CaMg(CO_3)_2$, a double carbonate compound belonging to the trigonal system (space group *R*-3) because of its yet unclear behavior in various depositional environments and its stability conditions. The goal of this research was to obtain the elastic properties of the mineral in terms of the second-order elastic moduli (4^{th} rank stiffness tensor) and *PV* equation of state formalism. In this context, Density Functional Theory (DFT) approaches represent an interesting instrument for the investigation of minerals that can potentially predict important physical-chemical properties through atomic-scale simulations. In this study, it was employed the CRYSTAL code (Dovesi et al., 2020), which implements both the Hartree-Fock and DFT frameworks, while benchmarking 12 different functionals (Hamiltonians) for the calculation of the elastic properties of dolomite. The second order elastic moduli were obtained from stress-strain relationships based on the total energy of the mineral as a function of a set of deformation, including the nuclear relaxation term from internal-strain tensor (Erba, 2016). A first assessment of the mechanical properties has determined the strongly anisotropic and directional dependency of the elastic properties due to the heterodesmic nature of dolomite caused by mixed covalent-ionic bonds described by Ca^{2+} and Mg^{2+} ions octahedrally coordinated by the oxygen atoms of the $(CO_3)^{2-}$ anions, and alternatively stacked along the *c*-axis of the mineral. The equation of state (EOS) was obtained from the total energy calculated for 7 unit cell volumes between 90% and 109% of the equilibrium (0 GPa) volume, and the E(V) data was fitted with a volume-integrated third-order isothermal Birch-Murnaghan formulation. The bulk modulus (K) calculated from the stiffness tensor and the EOS formalism was consistent, with a mean difference of about -1%. All calculated results were compared with the experimental data reported in the literature, highlighting a good agreement between theory and experiments. It was observed that the calculated elastic moduli are intrinsically larger than the experimental ones because of the athermal condition of the simulations (0 K), whereas the experiments were carried out at ambient *PT* conditions. The knowledge of these properties fundamentally constraints the stability conditions of the mineral while pursuing towards a thorough knowledge of the thermodynamic mechanisms.

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Experimental constraints on the kinetics of the albite = jadeite + quartz reaction depending on grain size and reaction overstepping

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Keywords: kinetics, high-pressure, eclogitization.

The breakdown of end-member albite to jadeite + quartz delimits the stability of feldspars towards high pressure and is accompanied by densification of about 20% – shear stresses induced by similar volumetric changes may cause brittle failure related to intermediate-depth earthquakes (Yamato et al., 2022). Similarly, densification and deformation during eclogitization have implications on the strength and buoyancy of orogenic roots and the stability of mountain ranges over geological timespans (Austrheim, 1998). Furthermore, eclogitization is considered to be a sluggish process that requires significant reaction overstepping and may occur well beyond the equilibrium pressure–temperature conditions, and/or remain largely incomplete – in particular in fluid-deficient felsic crust (Palin et al., 2017). However, the kinetics of the albite = jadeite + quartz reaction is not known, in particular regarding the effects of grain size, pressure–temperature overstepping, and duration. To address this point, we conducted high-pressure experiments using a piston-cylinder apparatus housed at the Institute of Geosciences, JGU Mainz. Natural albite crystals were crushed and sieved into grain size fractions between 50 and 500 µm, loaded into Au-capsules and separated by Au-foils. In Stage I, pressure was initially set just below (< 1kbar) the albite = jadeite + quartz reaction threshold (Holland, 1980), and followed by heating to target temperature. In Stage II, pressure was increased while maintaining constant temperature to variable target pressure above the reaction in order to estimate the effect of reaction overstepping. The samples where then quenched by power shutdown. Reaction progress was assessed using a scanning electron microscope (BSE) and/or a Raman spectrometer based on the observed fractions of reactant albite and products jadeite–quartz. Preliminary observations show that all experiments conducted so far, display at least partial reaction progress. Jadeite–quartz always occur as finely intergrown symplectites, typically decorating albite grains at the rims. The coupled data of P(T)-overstep, grainsize and experimental runtime is used to determine the effective reaction rate of the albite-breakdown, yielding end-member constraints on the kinetics of high-pressure transformation of fluid-deficient, coarse-grained felsic rocks that constitute the bulk of well-known (U)HP terranes such as the Western Gneiss Region (Norway) and the Dabie–Sulu (China).

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Amphiboles under extreme pressure: potassic-richterite, eckermannite and the role of polysomatism

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Keywords: amphibole, high pressure, polysomatism.

Potassic-fluoro-richterite, with end-member composition $K(NaCa)Mg_5Si_8O_{22}F_2$, has the largest *P*-*T* stability field of any amphibole. Potassic-richterite $K(NaCa)Mg_5Si_8O_{22}(OH)_2$, also has an enormous *P*-*T* stability range. Laboratory experiments show that, on its own composition, potassic-richterite is stable to 13 GPa and 1350 °C. In Nature, potassic-richterite is often present in peridotite xenoliths in kimberlites and is occasionally found as an inclusion phase in diamonds. Both modes of occurrence are consistent with its very high *P*-*T* stability determined experimentally.

While the lower *P*-*T* limit of potassic-richterite stability extends to ~0.1 GPa ($T \sim 900$ °C), in aluminous lherzolites phlogopite is the stable potassic phase below 7 GPa. At higher *P*, potassic-richterite is formed by the reaction of phlogopite and diopsidic clinopyroxene (Luth, 1997); for these rocks the maximum *P* stability of potassic-richterite is ~13 GPa. The potassic-richterite-forming reaction of diopsidic pyroxene + phlogopite relates fundamentally to the energetics of polysomatism.

A further interesting discovery from high-*P*-*T* experiments on peridotitic compositions (Konzett & Japel, 2003) was the occurrence of a mixed-chain < 2,1 > amphibole + pyroxene clinopyribole above the stability field of potassic-richterite, again pointing to the role of polysomatic behaviour in amphibole high-*P* stability. This pyribole is essentially a polysomatic mixture of potassic-richterite and omphacitic pyroxene structure modules.

There is also experimental evidence that eckermannite $NaNa_2Mg_4AlSi_8O_{22}(OH)_2$ may be a significant high-*P* amphibole. It has been suggested that it is the post-glaucophane sodium amphibole at $P > 4$ GPa (Howe et al., 2018). The stability field and limiting reactions of eckermannite have not been determined. Polysomatism may also play a role in the high-*P* stability of this amphibole.

In this presentation I will summarise our knowledge of the crystal chemistry of potassic-richterite and eckermannite and describe recent progress in studying their high-pressure behaviour. A key component of the crystal chemistry of these amphiboles concerns polysomatism, which links to their high-*P* stability.

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Effect of cation disorder on the high pressure behavior of ankerite

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Keywords: carbonates, cation disorder, high pressure.

The complex stability fields of carbonates extend from ambient up to high pressure (H*P*) – high temperature (H*T*) conditions, being strongly influenced by both chemical composition and cation ordering. In particular, the Fe-bearing carbonates and, among them, ankerite $Ca(Fe_xMg_{1-x})(CO_3)_2$ ($0 \leq x \geq 0.7$), gained particular interest as Fe-bearing phases in the Earth's interior. Ankerite, isostructural to dolomite, undergoes several phase transitions dependent on pressure (*P*) and (*T*). The order–disorder phase transition occurs at a critical *T* (*T*c) that is a function of Fe-content (Franzolin et al., 2012), where ankerite space group changes from *R*-3 (dolomite-like) to *R*-3*c* (calcite-like). At H*P*, carbonates in the dolomite-ankerite series undergoes phase transitions to H*P* polymorphs whose crystal structure depends on both Fe content and disorder degree (e.g., Merlini et al., 2017; Zucchini et al., 2025). The experiments presented here were carried out on two ankerite samples, $Ca_{1.0(2)}[Mg_{0.3(1)}Fe_{0.7(1)}](CO_3)_2$ (Ank7) $Ca_{1.0(2)}[Mg_{0.6(1)}Fe_{0.3(1)}Mn_{0.1(1)}](CO_3)_2$ (Ank3), which were used for annealing experiments and ex-situ crystal structure characterization at *T* conditions 450–800 °C for Ank7 and 700 – 1000 °C for Ank3. The order–disorder phase transition was achieved at the highest *T* in both samples, demonstrating that *T*c decreases with increasing Fe content. H*P* single-crystal X-ray diffraction experiments were performed on fully ordered and fully disordered Ank7 and Ank3 samples at the ID15B beamline (ESRF, Grenoble, France), up to ~50 GPa. Preliminary results show that ordered ankerite undergoes phase transition to ankerite-II, with the transition *P* decreasing with increasing Fe content (~13 GPa in Ank7 and ~15 GPa in Ank3). In the *P* range 37–40 GPa, Ank7 transforms to a rhombohedral ankerite-IIIb (Merlini et al., 2016) while Ank3 undergoes a phase transition to a triclinic structure for which structure refinements are in progress. During decompression, both Ank7 and Ank3 recover their original *R*-3 symmetry and high crystallinity. As for the disordered structures, the transition to ankerite-II was observed at *P* higher than those observed for the ordered crystals (more than 10 GPa), with transition *P* that seems to increase with increasing Fe content. Both order-disorder and H*P* phase transitions strongly influence the compressibility behavior of ankerite, with ordered ankerite-I and ankerite-II being the most and least compressible structures, respectively, while disordered ankerite lies in between (Zucchini et al., 2025).

The present study is aimed at giving a contribution to understanding the stability and compressional behavior of ankerite as a function of Fe content and cation distribution under typical mantle conditions. Depending on the subduction regime, these conditions may be suitable (warm subduction) or not (cold subduction) for the order-disorder phase transition with important implications on the ankerite's stability and elastic behavior.

Franzolin E. et al. (2012) - The temperature and compositional dependence of disordering in Fe-bearing dolomites. Am. Mineral., 97, 1676-1684, https://doi.org/10.2138/am.2012.4126.

Merlini M. et al. (2016) - High-temperature and high-pressure behavior of carbonates in the ternary diagram $CaCO_3$-$MgCO_3$-$FeCO_3$. Am. Mineral., 101, 1423-1430, http://doi.org/10.2138/am-2016-5458.

Merlini M. et al. (2017) - Dolomite-IV: Candidate structure for a carbonate in the Earth's lower mantle. Am. Mineral., 102, 1763-1766, http://dx.doi.org/10.2138/am-2017-6161.

Zucchini A. et al. (2025) - Influence of cation disorder on the mineral physics of ankerite. Am. Mineral., 110, 908-918, https://doi.org/10.2138/am-2024-9495.

S4.

Metamorphic petrology and petrochronology - reading and learning at the library of crustal rocks

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A further step forward towards establishing garnet as part of the *in-situ* U-Pb geochronology repertoire

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Keywords: in situ garnet dating, granulite, lower continental crust.

Accessory minerals provide chronometric data that are linked to key rock-forming minerals through petrographic context and geochemical fingerprints to tie the age and duration of rock-forming processes to pressure and temperature conditions. However, our ability to unravel *P–T–t* paths of high-grade metamorphic terranes is limited. Accessory mineral dates are often complex in migmatitic and granulitic samples, and the decoupling between ages and composition is common under high to ultra-high temperature conditions. Moreover, the behavior of accessory minerals in melt-bearing rocks is not fully understood, because migmatites and granulites are the sites of both melt generation, migration, accumulation and loss.

As a recorder of tectonometamorphic context during its growth, garnet has the potential to become the ultimate petrochronometer. Yet, *in-situ* garnet dating is still in its infancy. In this study, we applied the novel technique of *in-situ* U-Pb dating of garnet to the archetypal lower continental crust of the Ivrea-Verbano Zone (IVZ), NW Italy. In the IVZ, the temporal relationship between granulite-facies metamorphism and mafic underplating has long been debated, because of the interplay between tectonic, magmatic, metamorphic and metasomatic processes over a period of more than a hundred million years. Garnet from pelitic and mafic granulites yielded U-Pb ages between 287.4±4.9 Ma and 279.7±8.9 Ma, overlapping the timescales proposed for the emplacement of the Mafic Complex (285–281 Ma). These results indicate that the thermal climax in granulitic rocks was caused by mafic underplating and concomitant asthenospheric upwelling, rather than being inherited from the post-Variscan Carboniferous evolution. This study demonstrates the strength of garnet petrochronology in resolving complex tectono-metamorphic-magmatic histories of high-grade terrains.

Sm-Nd isotopic architecture of the Calabria crustal section (Southern Italy): a view from whole-rock and *in-situ* analyses

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Keywords: accessory minerals, Nd isotopes, crustal differentiation.

New Phanerozoic continental crust is mainly formed in magmatic arc contexts and can then be reworked by tectonic, magmatic and metamorphic processes during late orogenic stages. These geological processes shape the continental crust and are responsible for its stratified structure, leading to intra-crustal differentiation. In most collisional/post-collisional environments, a wide variety of granitoids can be generated including granitoids with hybrid signature (mantle-crust sources) and pure crustal S-type granites. The exact contribution of mantle and crust components is however difficult to quantify and several studies (e.g. Couzinié et al., 2016) suggested that some of the geochemical proxies, extensively used to quantify them (e.g. Hf isotopes in zircon), can largely underestimate the mantle component in post-collisional magmas. Another limitation on our abilities to untangle the sources that participate in the construction of the crust is related to the difficult accessibility of the continental crust roots where important melting and hybridisation processes occur.

Here, we present an extensive dataset of Sm-Nd isotopic measurements along a 26 km-thick crustal section in Calabria (Schenk, 1990). The main aim is to characterise the Sm-Nd isotopic variability at various scales (outcrop, thin-section, mineral) and to investigate hybridisation and lower crustal processes. The Serre crustal section exposes partially melted lower crustal rocks (mafic and felsic granulites, migmatitic paragneisses) and middle crustal granitoids forming a 13-km thick batholith and constituting the final products of crustal differentiation. They mainly formed and emplaced during the final stages of the Variscan orogeny following decompression and extensive partial melting of the lower crust. Results show that the lower crust is strongly heterogeneous (with whole-rock $\varepsilon Nd_{290\ Ma}$ = -10.5 to +1.7) at various scales (from whole-rock to mineral), whereas the mid-crustal granitoids reveal a striking homogeneity with a strong crustal signature (average $\varepsilon Nd_{290\ Ma}$ close to -7). Hybridisation processes between mafic rocks and anatectic melts are clearly identified using *in-situ* Sm-Nd isotopes coupled with trace element analyses on accessory minerals. They are particularly vigorous in a narrow zone (1-2 km) located at the transition from the lower to the middle crust.

Finally, an ongoing project aiming at developing protocols for *in-situ* analyses of iron and magnesium stable isotopes applied to the Calabria crustal section is presented.

Couzinié S. et al. (2016) - Post-collisional magmatism: crustal growth not identified by zircon Hf–O isotopes. Earth Planet. Sci. Letters., 456, 182-195, https://doi.org/10.1016/j.epsl.2016.09.033.

Schenk V. (1990) - The exposed crustal cross section of southern Calabria, Italy: Structure and evolution of a segment of hercynian crust. In: Salisbury M.H. & Fountain, D.M. (Eds), Exposed Cross-Sections of the Continental Crust, Nato ASI series, 317, 21-42, https://doi.org/10.1007/978-94-009-0675-4_2.

Breaking the garnet: triggering processes for atoll-shaped garnets formation

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Keywords: atoll-shaped garnet, garnet fracturing, fluid circulation.

Atoll-shaped garnet refers to garnet crystals displaying partially resorbed cores, which are commonly replaced by newly formed garnet or other mineral phases (Cheng et al., 2007). These microstructures occur in several lithotypes and encompass widespread tectono-metamorphic environments (i.e., different ranges of chemistry, P, T and fluid availability conditions), from subduction to lower crust settings (Maffeis et al., 2025; Dong et al., 2018). Several models have been proposed to explain atoll garnet formation, the most widely accepted of which involves dissolution of the garnet core facilitated by fluid circulation. However, the mechanisms that trigger garnet fracturing, allowing reactive fluids to penetrate the core, remain unclear and debated.

This study aims to provide new insights into the effective mechanism for garnet fracturing and subsequent atoll formation. We focus on atoll garnets hosted in omphacite-veined eclogite from the Monviso Massif (Western Alps). These rocks developed in meta-ophiolites involved in a cold subduction, characterized by low thermal gradients and a large fluid availability. Mineralogical and petrological analyses were conducted by using micro-Raman spectroscopy, SEM-EDS, EBSD and LA-ICP-MS to characterize garnet microstructural features, chemical zoning, and deformation patterns.

These observations were compared with data from atoll garnets formed in different geodynamic settings to identify common features, such as chemical composition (e.g., grossular rich) and occurrence of several inclusions (i.e., hydrate minerals) in preserved garnet cores. Our findings point to the key role of the atoll formation processes in the weakening and strain localization of rocks.

Cheng H. et al. (2007) - Origin of atoll garnets in eclogites and implications for the redistribution of trace elements during slab exhumation in a continental subduction zone. Am Mineral, 92, 1119-1129, https://doi.org/10.2138/am.2007.2343.

Dong J. et al. (2018) - Metamorphic Evolution During Deep Subduction and Exhumation of Continental Crust: Insights from Felsic Granulites in South Altyn Tagh, West China. J. Petrol., 59(10), 1965-1990, https://doi.org/10.1093/petrology/egy086.

Maffeis A. et al. (2025) - Filling the gap in the UHP metamorphic record of the Liguro-Piemont Lower unit: insights on fluid-mediated formation of atoll garnets. Lithos, 498-499, 107981, https://doi.org/10.1016/j.lithos.2025.107981.

Evaluating the radiogenic heat production of anatectic melts

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Keywords: melt inclusions, heat production, deep crust.

The model of crustal differentiation via anatexis and extraction of anatectic melts to shallower levels, producing a residual lower crust and an upper crust enriched in incompatible elements, implies an overall decrease of radiogenic heat production with depth (Rudnick & Gao, 2003). Phase equilibria modelling coupled with solubility expressions for accessory minerals is often used to support the view that melt loss leads to a depletion of heat-producing elements (HPE - U, Th, and K) in the residuum, because the anatectic melt is assumed to be saturated in these elements (Yakymchuk & Brown, 2014). However, some empirical studies of the radiogenic heat production (HP) of deep crustal levels now exposed at the surface show a different picture, because similar, high heat production values have been measured in rocks at both sub- and suprasolidus conditions (Alessio et al., 2018).

Because anatectic melt inclusions (MI) may record the pristine composition of melts produced in the lower continental crust, they may provide further insights into this debate. Here, we evaluate K_2O, Th, and U data and calculate the HP from 13 case studies worldwide (10 of metasedimentary origin and 3 of mafic origin, with peak temperatures ranging from 700 to 1000 °C). MI are compared with a granite database and model predictions. The comparison clearly shows similarities in the behavior of MI and granites. An asymmetric distribution with a shift toward lower values is observed for U and HP. The most significant discrepancy is observed for Th. Instead, a remarkable difference is observed for both U and Th when the MI data set is compared with model predictions. The MI data suggest that depletion of HPE in the deep crust should occur within the source terrain during melt generation, but only ultrahigh-temperature (UHT) metamorphism and formation of UHT anatectic melts may mobilize sufficient amounts of HPE, resulting in a HPE-depleted residual lower crust.

Alessio K.L. et al. (2018) - Conservation of deep crustal heat production. Geology, 46(4), 335-338, https://doi.org/10.1130/G39970.1.

Rudnick R.L. & Gao S. (2003) - Composition of the continental crust. In: Rudnick R.L. (Ed), Treatise on Geochemistry, Volume 3, 1-55,. Elsevier Ltd., http://doi.org/10.1016/B978-0-08-095975-7.00301-6.

Yakymchuk C. & Brown M. (2014) - Behaviour of zircon and monazite during crustal melting. J. Geol. Soc., 171(4), 465-479, https://doi.org/10.1144/jgs2013-115.

The non-cubic garnets in the graphitic metapelites of the Glockner Nappe (Senges valley, SW Tauern Window, Eastern Alps, Italy)

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Keywords: garnet, low-T metamorphism, polychromatic polarization.

Prompted by the study of Masè (1965), who collected garnetiferous graphitic schists which turned out to contain optically anisotropic garnets, we conducted a systematic sampling campaign in the area of Valle di Senges, between Lago Selvaggio and Giogo di Trens, north of Mules (Alto Adige). More than fifty samples of garnet-bearing schists have been collected from the outcrops mapped by Schiavo et al. (2015) and belonging to the "Ophiolitic Glockner nappe", which corresponds to the Obereschieferhulle *Auct*. Mostly made of calcschists and impure marble, the Glockner nappe contains also minor phyllites and garnet schists.

The studied samples are graphitic garnet-bearing phyllites and schists, metamorphosed during the Alpine orogenesis. Along with chlorite, muscovite, garnet, quartz, ilmenite and graphite, they may contain biotite and more rarely chloritoid.

Garnet has diametre up to 6 mm and ranges in shape from euhedral to dendritic. In places it appears to grow with a lobate, flower-like structure. Crystals can be inclusion-free or contain abundant inclusions mostly of quartz and graphite. Observed under polychromatic polarization microscopy (Cesare et al., 2022), garnets in all samples display optical anisotropy, with spectacular examples of both the sector zoning and the "mottled" pattern described by Cesare et al. (2019).

Chemically, the almandine-rich garnets are strongly zoned with a pronounced bell-shaped profile of spessartine, with grossular around 20% and very low pyrope. A typical such growth zoning pattern has core $Alm_{48}Sps_{31}Grs_{18}Pyr_{03}$ and rim $Alm_{68}Sps_{07}Grs_{19}Pyr_{06}$. Quantification of OH in the garnets by FTIR has been conducted on crystals from two samples. Results provide OH values in the range or lower than other almandine-rich garnets in the literature, supporting the conclusion that garnet anisotropy is not due to a hydrogarnet component.

The temperature of metamorphism and garnet growth has been estimated by Raman spectroscopy of carbonaceous matter, due to the presence of graphite in all samples. Results are in the range 400-500 °C.

Crystals with the best developed optical sector zoning will be characterized by single-crystal X-ray diffraction.

The studied samples and garnets add to the long record of occurrences of non-cubic common garnets from low-T metamorphic rocks worldwide. And support the theory that at low metamorphic grade garnet does not grow as a cubic mineral.

Cesare B. et al. (2019) - Garnet, the archetypal cubic mineral, grows tetragonal. Scientific Reports, 9(1), 14672.

Cesare B. et al. (2022) - Polychromatic polarization: Boosting the capabilities of the good old petrographic microscope. Geology, 50(2), 137-141.

Masè G. (1965) - Lineamenti geologico-petrografici della "Cupola di Senges" (Vipiteno, Alto Adige). Tesi di Laurea, Università di Padova.

Schiavo A. et al. (2015) - Geology of the Brenner pass-fortezza transect, Italian Eastern Alps. J. Maps, 11(1), 201-215.

Petrological and petrochronological study of the graphitic schists ("*Furtschaglschiefer*") of Passo di Vizze (SW Tauern Window, Eastern Alps, Italy)

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Keywords: Eastern Alps, metapelites, petrochronology.

Furtschaglschiefer is a layer of graphitic schists belonging to the Greiner unit in the western Tauern Window. The tectonostratigraphic attribution of these rocks is debated, but they are considered the post-Variscan cover of the Zillertal-Riffl Nappe, metamorphosed only during the Alpine orogeny. These schists display a peculiar structure, where biotite adds to garnet to form porphyroblasts up to 1 cm long defining a marked lineation. The mineral assemblage of the schists comprises quartz, plagioclase, garnet, biotite, ilmenite, muscovite, graphite ± chlorite ± epidote ± staurolite.

Garnet occurs as (non cubic, Cesare et al., 2019) euhedral dodecahedra 2-3 mm in diameter. Biotite occurs in three textural generations, whose microstructures and origin are the subject of a companion contribution (Salvadori et al., 2025).

The schists are chemicallly well-equilibrated, the only zoned phase being almandine-rich, with X_{Alm} increasing from ~65% at the core to ~80% at the rim. Biotite has an X_{Mg} in the overall range 0.45-0.60, with TiO_2 contents up to 2.3 wt%, and its composition is homogeneous within each sample. Chlorite has an average X_{Mg} of 0.6. The bulk composition is less aluminous than the worldwide median pelite, with variable X_{Mg}, in the range 0.32-0.52. The total organic carbon (TOC) is 0.3-0.4 wt.%. Bulk rock and mineral compositions indicate that disappearance of chlorite in the less magnesian compositions was related to the continuous AFM reaction Chl = Grt+Bt.

Micro-Raman spectroscopy of carbonaceous material (RSCM) was applied to estimate the peak metamorphic temperatures, and four samples provided overlapping values of 550±50 °C, consistent with Bt-Grt geothermometric estimates obtained by Selverstone et al. (1984). Thermodynamic modelling was performed on 4 samples in both MNCKFMASHT and MNCKFMASHTO, using both hp04ver and hp62ver datasets. The observed Bt-Ms-Ilm-Grt-Pl-Qz-Gr assemblage is predicted stable in a wide field (500-650 °C, 4-10 kbar), but predicted and measured compositions do not match in it, with significant to huge mismatch for X_{Mg} of Bt and Grt.

Therefore, while metamorphic T can be reliably constrained by RSCM, pressure estimates are still poor, and at present there is no evidence of significant decompression from higher-P conditions predating the development of the main Grt-Bt-Ilm±Chl assemblage. *In situ* U-Pb dating of garnet by LA-MC-ICPMS was successfully performed on two samples, providing ages 25.11±0.82 and 24.08±1.14 Ma. These ages, 5 m.y. younger than those determined by Rb-Sr geochronology on large garnets in adjacent outcrops (Christensen et al., 1994), rejuvenate the age of peak conditions of the Oligocene amphibolite-facies metamorphism in this part of the Tauern Window.

Cesare B.et al. (2019) - Garnet, the archetypal cubic mineral, grows tetragonal. Sci. Rep., 9(1), 14672.

Christensen J.N. et al. (1994) - Correlation by Rb-Sr geochronology of garnet growth histories from different structural levels within the Tauern Window, Eastern Alps. Contrib. Mineral. Petrol., 118, 1-12.

Salvadori L. et al. (2025) - Microstructural study of the graphitic schists "Furtschaglschiefer" of Passo di Vizze (SW Tauern Window, Eastern Alps, Italy). Congresso congiunto SIMP-SGI, Padova 2025.

Selverstone J. et al. (1984) - High-pressure metamorphism in the SW Tauern Window, Austria: PT paths from hornblende-kyanite-staurolite schists. J. Petrol., 25(2), 501-531.

Deformation control on OH distribution at the nanoscale

Corvò S.*[1-2], Chen Y-S.[3-4], Holmes N.[3-4-5], Förster M.W.[6], Yaxley G.[6], Maino M.[1-2], Langone A.[1], Cairney J.[3-4] & Piazolo S.[7]

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Keywords: NAM, APT, PiFM.

In recent decades, titanite has gained popularity in the petro- and micro-structural community due to its advantageous microstructural and compositional properties that make it an important tracer of fluids, chemical reactions and deformation mechanisms in the Earth's crust. Thanks to its crystal structure, titanite incorporates a wide range of minor and trace elements, including OH, the equivalent chemical component of water. Indeed, although titanite is considered a nominally anhydrous mineral (NAM), it can incorporate significant amounts of OH (up to 0.1 wt.%). Understandings of hydrogen concentration, which constitutes the water molecule, in titanite is important since it can affect the physical and chemical properties of minerals and rocks of the upper mantle/lower crust, such as deformation mechanisms, rheology and fluid flow. Moreover, these studies could be useful to understand the reservoirs and the water cycle in the Earth system. Nevertheless, advanced studies regarding water content in titanite are still lacking. However, thanks to recent improvements in both petrochronological and microstructural techniques, the investigation of the link between hydrogen mobility and deformation processes at the nanoscale is now possible. In this study, we combined the Atom Probe Tomography (APT) to obtain 3D maps showing the distribution of OH with Photo-induced Force Microscopy (PiFM) to quantify the concentrations of OH in selected deformed and undeformed domains of mylonitic titanite (Corvò et al., 2023). Specifically, we investigate OH variations between titanite domains showing different dislocation densities in rock layers with different composition (amphibolite vs calcsilicate). Preliminary results indicate that OH contents vary between the titanite grains from the two different compositional layers with a positive correlation between OH and dislocation densities, suggesting a heterogeneous distribution of water controlled by i) dislocation creep, and ii) the bulk rock composition. This study highlights the importance of a multi-technique and multi-disciplinary approach to advance our understanding on the deformation/chemical processes occurring at the nanoscale ultimately governing the large scale rheological and chemical evolution of rocks during major tectonic events.

Corvò S. et al. (2023) - Crystal plasticity and fluid availability govern the ability of titanite to record the age of deformation. Earth Planet. Sci. Letters, 620, 118349.

Heterogeneous deformation and partial (re-)equilibration of orthogneiss in the Dora-Maira Massif (Western Alps)

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Keywords: Dora-Maira, thermodynamic modelling, orthogneiss.

Orthogneiss are widespread in continental crystalline basements (Chapman et al., 2019; Massonne, 2021) and are often considered less reliable and useful than metabasites and metapelites when reconstructing metamorphic P–T evolutions (Massonne, 2015; 2021). This is primarily due to their frequent tendency to record incomplete metamorphic equilibration, even under high-temperature conditions (e.g., Oberhänsli et al., 1985; Chapman et al., 2019).

In this contribution, we investigate a suite of orthogneiss derived from the same Lower Paleozoic magmatic cycle, cropping out in the central Dora-Maira Massif (Western Alps), providing a natural laboratory to examine the interplay between deformation, fluid availability, and metamorphic re-equilibration during the deformation of granitic rocks.

The studied orthogneiss recorded variable degrees of Alpine deformation and metamorphic re-equilibration, varying from low-strain domains – preserving pre-Alpine features and recording a scarce Alpine metamorphic overprint - to high-strain, mylonitic to ultramylonitic, portions that experienced a complete metamorphic re-equilibration during the Alpine cycle. Microtectonics and geochemical mass transfer analyses are used to reconstruct the microstructural and chemical evolution of the studied orthogneiss from the low-strain towards the high-strain domains. Mineral chemistry and thermodynamic modelling of selected samples are integrated to constrain the Alpine metamorphic evolution of the high-strain domains and assess the control of deformation mechanisms, fluid influx, and rheological heterogeneities in the preservation or obliteration of the pre-Alpine mineral assemblage.

Our results show that when low-strain domains in orthogneiss are affected by fluid-deficient conditions, their deformation and metamorphic re-equilibration are limited, and high-pressure (HP) mineral assemblages are usually poorly developed. However, ductile shear zones can act as preferential pathways for fluids during deformation under water-saturated conditions, promoting recrystallization and facilitating metamorphic (re-) equilibration. This process enabled the high-strain domains in orthogneiss to equilibrate under HP eclogitic-facies conditions.

Chapman T. et al. (2019) - Inefficient high-temperature metamorphism in orthogneiss. American Mineralogist: J. Earth Planet. Mater., 104(1), 17-30.

Massonne H.J. (2015) - Derivation of P–T paths from high-pressure metagranites—Examples from the Gran Paradiso Massif, western Alps. Lithos, 226, 265-279.

Massonne H.J. (2021) - Key patterns of S-type granitic gneiss to define the baric (low-to high-pressure) nature of Phanerozoic basement terranes. Terra Nova, 33(3), 225-239.

Oberhänsli R. et al. (1985) - Geochemistry, geochronology and petrology of Monte Mucrone: an example of Eo-Alpine eclogitization of Permian granitoids in the Sesia-Lanzo Zone, Western Alps, Italy. Chem. Geol.: Isotope Geosci. Sec., 52(2), 165-184

Tectonic architecture and metamorphic evolution of the Pinerolo-Sanfront Unit (Northern Dora-Maira Massif, Western Alps)

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Keywords: Dora-Maira, metamorphism, structural evolution.

The Dora-Maira Massif is a major tectonic complex exposing units of continental basement stacked at different structural levels in the internal Western Alps. It extends from the Maira Valley, to the South, to the Susa Valley, to the North, bounded to the East mainly by sediments of the Po Basin and overlain to the West by oceanic-derived Penninic units. This crystalline massif has long captured the attention of geologists and renovated interest arrived since the discovery of ultra-high-pressure (UHP) metamorphism by Chopin 1984. Over the years, numerous petrological and metamorphic studies have focused on constraining the evolution of the different units comprising the Dora-Maira Massif, especially in its southern portion (Groppo et al., 2025). The northern-central portion of the Dora-Maira Massif is composed of a stack of three tectonic units, from geometric bottom to top: the Pinerolo-Sanfront Unit, the Chasteiran Unit, and the Muret Unit. Although previous studies have significantly advanced our understanding of this sector (Nosenzo et al., 2024), several key questions remain open, particularly regarding the metamorphic and structural evolution of the structurally lower units.

In this contribution, we present new metamorphic and structural data collected within the framework of the CARG geological mapping project (Sheet 172 – Pinerolo), with a focus on the Pinerolo-Sanfront Unit.

Based on our field and microstructural observations a complex polyphase deformation history comprising at least three different tectono-metamorphic events is highlighted: i) the earliest phase (D1) is recorded by a foliation (S1), preserved only within microlithons, or internal foliation of porphyroblasts, and in the most competent lithologies; ii) a second tectono-metamorphic phase (D2) characterised by isoclinal folds with an E-W trending axis associated to an (S2) axial plane foliation, and iii) the third deformation phase (D3) associated with open to tight folds, with an E-W trending axis, is associated to a S3 crenulation cleavage which is in serval areas the main foliation. To reconstruct its complex and still poorly constrained metamorphic history (Avigad et al., 2003; Groppo et al., 2025), we provide new metamorphic observations based on two representative micaschist samples, our results show a peak P-T conditions in the upper blueschist-facies. Finally, to better constrain the timing of the development of the S3 foliation preliminary $^{40}Ar/^{39}Ar$ dating on white mica are presented.

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Chopin C. (1984) - Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. Contrib. Mineral. Petrol., 86, 107-118.

Groppo C. et al. (2025) - A New UHP-HP Tectono-Metamorphic Architecture for the Southern Dora-Maira Massif Nappe Stack (Western Alps) Based on Petrological and Microstructural Evidence. J. Metam. Geol., 43(4), 359-383.

Nosenzo F. et al. (2024) - Tectonic architecture of the northern Dora-Maira Massif (Western Alps, Italy): field and geochronological data. Swiss J. Geosci., 117(1), 6.

Tectono-metamorphic evolution of the Simplon Pass area: new insights from geological mapping and P-T data with implications for the Gälmji Zone (Central Alps, Switzerland)

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Keywords: Central Alps, tectono-metamorphic evolution, P-T-D paths

We present new structural and tectono-metamorphic data from the Simplon Pass region in the Central Alps (Switzerland), where the deepest units of the Alpine belt experienced Cenozoic Barrovian metamorphism. This area (Steck, 2008) offers an excellent exposure of the footwall of a regional-scale Low-Angle Normal Fault (LANF), known as the Simplon Fault Zone. The footwall comprises several tectonic units, including the Berisal Unit and the Gälmji Zone (Middle Penninic), the Sion-Courmayeur Zone (Lower Penninic), and the Monte Leone Unit (Lepontic Domain). In contrast, the only unit occurring in the hanging wall is the Zone Houillère, part of the Middle Penninic.

Fieldwork conducted led to the following results: (i) the creation of a new 1:10,000-scale geological-structural map, and (ii) the reconstruction of Pressure–Temperature–Deformation (P–T–D) paths using microtectonic analysis and thermodynamic modeling. P–T conditions and P–T–D paths for samples from different tectonic units were determined through pseudosection calculations in the MnNKCFMASHT system. Evidence for a pre-Barrovian high-pressure (HP) metamorphic stage was found in multiple units, suggesting an Alpine HP event with $P \geq 1.6$ GPa and $T < 450$–500 °C. The subsequent Barrovian metamorphic stage reached peak conditions of 0.8–1.0 GPa and 550–600 °C.

Our integration of field observations with meso- and microstructural and metamorphic data reveals that the boundaries of the so-called “Gälmji Zone” are poorly defined. Therefore, classifying the Gälmji Zone as a distinct tectonic unit is not straightforward and further evidence should be collected. We propose that the Gälmji Zone may instead represent part of the Sion-Courmayeur wildflysch, within the Sion-Courmayeur Zone, located at the same structural level between the Monte Leone and Berisal units. If this interpretation holds, it would imply that the Gälmji Zone consists of large blocks tectonically eroded from overlying units during subduction. Further research is required to better constrain the Alpine HP event and clarify the structural interpretation of this region.

Steck A. (2008) - Tectonics of the Simplon massif and Lepontine gneiss dome: deformation structures due to collision between the underthrusting European plate and the Adriatic indenter. S. J. Geosci., 101, 515-546.

Metamorphic architecture along the Pellice Valley (Cottian Alps) revealed by the RSCM geothermometry

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Keywords: Western Alps, RSCM, metamorphism.

The Pellice Valley (Cottian Alps) represents a geological transect of the Western Alps, where a composite stack of both oceanic and continental units crops out. Here, metamorphic rocks formed at high- to (ultra high)-pressure, low-temperature conditions during subduction are exceptionally well preserved. Four main tectonic units divided by major tectonic contacts, were identified based on a new geological map, carried out at the scale of 1:8000. From bottom to top, they are: (i) Muret Unit (a continental-derived unit composed mainly of micaschist and orthogneiss), (ii) Cima Lubin-Roccenie-Colle Giulian Unit, constituted by a calcschist matrix enveloping continental and oceanic derived bodies, (iii) meta-ophiolitic Monviso Unit s.l., and (iv) the meta-sediment dominated Albergian-Mirabouc-Bouchet Unit.

Petrographic observations of oriented samples have highlighted a partly diachronous tectono-metamorphic evolution. The application of Raman Spectroscopy of Carbonaceous Material (RSCM) (Beyssac et al., 2002) technique provided new geothermometric data, enabling to constrain the "peak" temperatures (T_{max}) in the mapped metasediments for each unit along the transect. The new RSCM data refined the peak temperature trends within the Albergian-Mirabouc-Bouchet Unit (increasing eastwards from ca. 400 °C to c. 470 °C), comparable with the literature (Herviou et al., 2022) and with microstructural observations that testify blueschist facies conditions, attested by Ph, Qz, Rt, ± Cld, ± Lws and Gln (pseudomorphs) assemblages.

In the Monviso Unit s.l. the RSCM, in the garnet-chloritoid-bearing metasediments, has revealed T_{max} of ca. 500 °C. Serpentinites at the base of this Unit have an assemblage with Srp, Amp, Ol, Ilm and importantly, Ti-Chu, identified for the first time in the area, and testifying possible UHP conditions (Rebay et al., 2012; Luoni et al., 2018).

Metamorphic peak conditions in the Cima Lubin-Roccenie-Colle Giulian Unit are characterized by Tmax up to ca. 510 °C in agreement with observed peak paragenesis of Ph-Cld-Qz-Grt-Rt-Cb. T_{max}, ca. 470 °C are registered in the eclogitic Muret Unit, which appear lower than the estimates (530-560 °C) from polycyclic micaschists.

Beyssac O. et al. (2002) - Raman spectra of carbonaceous material in metasediments: a new geothermometer. J. Metam. Geol., 20(9), 859-871.

Herviou C. et al. (2022) - Subducted fragments of the Liguro-Piemont ocean, Western Alps: Spatial correlations and offscraping mechanisms during subduction. Tectonophys., 827, 229267.

Luoni P. et al. (2018) - UHP Ti-chondrodite in the Zermatt-Saas serpentinite: Constraints on a new tectonic scenario." Am. Mineral., 103(6), 1002-1005.

Rebay G. et al. (2012) - Interaction of deformation and metamorphism during subduction and exhumation of hydrated oceanic mantle: Insights from the Western Alps. J. Metam. Geol., 30(7), 687-702.

Phase equilibria in the CKFMAST-COH system applied to garnet-wollastonite calc-silicate rocks: (P-)T-X_{CO2} evolution and potential for solution models comparison

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Keywords: phase equilibria, calc-silicates, mountain belts.

Calc-silicate rocks are notorious for being amongst the most challenging rocks for petrological models to be employed. The chemical heterogeneity of their protoliths leads to the metamorphic growth of sometimes an exaggerated number of mineral phases. This, coupled with the current lack of activity-composition models directly calibrated to calc-silicate phases, can complicate the thermodynamic modelling of such rocks.

In the Variscan chain of Sardinia, garnet-wollastonite calc-silicate rocks hosted in andalusite-bearing metapelites represent good candidates for the modelling of calc-silicate assemblages. The area is characterized by a LP-HT regional metamorphism followed by contact metamorphism during granitoid intrusion, with andradite+wollastonite+vesuvianite growth in the calc-silicate rocks. The observed microstructures combined with mineral chemistry allowed us to reconstruct a prograde evolution characterized by the growth of phyllosilicatesàzoisiteàCa-amphiboleàK-feldspar and Mg-rich clinopyroxene (with minor plagioclase) àgrossular and epidoteàandraditeàwollastonite and vesuvianite. Minor phases are (relict) quartz and calcite, scapolite, titanite, apatite and johannsenite.

We explored isobaric (0.5 GPa) T-X_{CO2} petrogenetic grids in the CKFMAST-COH system to put further constrains on the T-X_{Fluid} evolution underwent by the samples. In the T-X_{CO2} space, the inferred reactions are crossed, during the prograde path, from ~435 ºC (zoisite-in) to ~640 ºC (wollastonite-in) with an X_{CO2} decrease from 0.56 to 0.13. The T-X_{CO2} invariant points associated to the grossular- and wollastonite-forming univariant reactions match with the assemblage Grt+Cpx+Qz+Wo+Ttn modelled in the T-X_{CO2} phase diagram, which is in turn consistent with the peak mineralogy observed in thin section. Peak temperatures at the wollastonite-in isograd are slightly lower than those reported for the neighbor migmatitic orthogneiss (680-700 °C / 0.32–0.46 GPa, Cruciani et al., 2022). Decompression and heating during granitoid intrusion led to the growth, between 650-720ºC, of andradite on grossular, epidote and clinopyroxene, vesuvianite on grossular and, possibly, further vesuvianite-consuming late wollastonite. Invariant points associated to andradite and vesuvianite-forming univariant reactions depicted from a second isobaric (0.25 GPa) T-X_{CO2} grid again match, in the T-X_{CO2} phase diagram, with the microstructural relationship and mineral assemblage observed in the samples.

Provided the good consistency of our (P-)T-X_{CO2} data with the regional metamorphic conditions of the area, we modelled our samples using different activity-composition (a-X) solution models. Our preliminary results may provide an useful background for i) a correct a-X models application in the thermodynamic modelling of calc-silicate rocks, and ii) future efforts regarding the calibration of new thermodynamic models for common calc-silicate phases such as for andradite-rich garnets, scapolite or vesuvianite.

Cruciani G. et al. (2022) - Hot metamorphic complex in the Foreland Zone of the Variscan chain: Insights from the Monte Filau orthogneiss (SW Sardinia), Italy. It. J. Geosci., 141(3), 385-399, https://doi.org/10.3301/IJG.2022.22.

U–Pb and *in situ* Rb–Sr geochronology to evaluate preservation of the Eoarchean record in the Narsaaq nunite, Itsaq gneiss complex, western Greenland

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Keywords: Eoarchean ultramafic rocks, In-situ phlogopite Rb–Sr dating, zircon U–Pb geochronology.

Geodynamic, metamorphic, and surface processes have extensively recycled, transformed, and eroded Eoarchean (3.6–4.0 Ga) rocks, leaving a sparse and fragmentary geological record. Nevertheless, it is from these rare rocks that we derive critical information about a key period in the evolution of Earth, when two processes unique to our planet first began: life and plate tectonics.

Rare Eoarchean rocks occur within cratonic complexes alongside Meso- and Neoarchean assemblages, often overprinted by Proterozoic high-temperature metamorphism. In the Eoarchean Itsaq Gneiss Complex (western Greenland), ultramafic lenses composed mainly of phlogopite-bearing dunites, with minor amphibole and rare orthopyroxene. Although their origin – whether as mantle peridotites or cumulates from Mg-rich melts – remains debated, these rocks are genetically linked to the Eoarchean mantle and may thus preserve insights into the processes active during the onset of plate tectonics.

New U–Pb and in situ Rb–Sr geochronology from the renowned Narsaaq dunite lens, associated gabbros, and crosscutting phlogopite-rich dikes and veins reveals a complex evolutionary history. U–Pb zircon data from the gabbro confirm the Eoarchean age of this lens. In contrast, zircons in phlogopite from dikes, veins, and interstitial domains within the olivine grains in dunite yield Neoarchean ages, consistent with the nearby peralkaline intrusions. In situ Rb–Sr dating on interstitial and vein-hosted phlogopite defines Proterozoic ages, likely reflecting localized Proterozoic shear zone activity, isotopic resetting, or both. These results indicate that the Narsaaq dunites were likely infiltrated by crustal melts during the Neoarchean, and subsequently underwent further transformation, which could be a limitation for understanding the most ancient processes in the history of Earth.

Constraining UHP timing in the Western Alps: preliminary results of *in situ* U-Pb dating on coesite-bearing garnet across the entire meta-ophiolite belt

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Keywords: garnet dating, coesite, Western Alps.

Tracing the distribution and timing of ultrahigh-pressure (UHP) metamorphism of different meta-ophiolite units provides crucial constraints on the dynamics and velocity of subduction and exhumation across the entire mountain belts. Worldwide, UHP tectono-metamorphic units are only a few and the availability of this type of combined study is limited. However, the recent discoveries of several UHP units in the Western Alps (Ghignone et al., 2023, 2024; Maffeis et al., 2025) make it the perfect natural laboratory for filling this gap and deciphering subduction-exhumation dynamics.

Here we present the preliminary results of the U-Pb dating on coesite-bearing garnets, carried out on five coesite-bearing localities of the Internal Piedmont Zone (IPZ), including from north to south: Lago di Cignana (Reinecke, 1991), Orco Valley, Susa Valley (Ghignone et al., 2024), Rocciavrè and Monviso (Ghignone et al., 2023). Orco Valley and Rocciavrè are reported here for the first time as coesite-bearing localities. A systematic sampling campaign along the entire Western Alpine, combined with a detailed study of inclusions in garnet with μ-Raman spectroscopy, allowed us to recognize and define the distribution of coesite-bearing UHP units. The targeted lithologies were metasediments (i.e., garnet–quartzite and garnet–chloritoid micaschist), which are the best rock types for preserving coesite and, locally, meta-mafic lithotypes (i.e., eclogite and garnet–metabasite). Coesite-bearing garnet domains were dated with *in-situ* U-Pb, a solid technique that provides an effective age of a mineral closely tied to the P–T history. Coesites Raman spectra contain the typical vibrational modes of the phase (521, 427, 271 and 180 cm^{-1}), slightly shifted due to elastic residual strain. In all the different UHP localities listed above and in the newly collected samples, the presence of coesite is limited to a specific garnet domain (e.g., core, mantle), pinpointing the stage of garnet growth at UHP conditions. All the other garnet domains instead contain quartz, and they are devoid of evidence of growth at UHP conditions.

The results reveal two distinct clusters of UHP metamorphic ages (40–45 Ma and 50–55 Ma) identified in different areas, suggesting a diachronous attainment of peak at UHP conditions across the IPZ. Our data provide new opportunities to better constrain tectonic models and advance our understanding of deep processes taking place along subduction zones.

Ghignone S. et al. (2023) - A new UHP unit in the Western Alps: first occurrence of coesite from the Monviso Massif (Italy). Am. Mineral., 108 (7), 1368-1375, https://doi.org/10.2138/am-2022-8621.

Ghignone S. et al. (2024) - Mineralogical and petrological constraints and tectonic implications of a new coesite-bearing unit from the Alpine Tethys oceanic slab (Susa Valley, Western Alps). Lithos, 472, 107575, https://doi.org/10.1016/j.lithos.2024.107575.

Maffeis A. et al. (2025) - Filling the gap in the UHP metamorphic record of the Liguro-Piemont Lower unit: insights on fluid-mediated formation of atoll garnets. Lithos, 498-499, 107981, http://doi.org/10.1016/j.lithos.2025.107981.

Reinecke T. (1991) - Very-high-pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas zone, Western Alps. Eur. J. Mineral., 3, 7-17, https://doi.org/10.1127/ejm/3/1/0007.

Liquid immiscibility generates anatectic carbonatites from meta-marls in orogenic settings

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Keywords: anatectic carbonatites, liquid immiscibility, meso- and micro-structures.

The genesis of anatectic carbonatites – i.e., carbonate-rich igneous rocks crystallized from crustal-derived carbonate melts (Yaxley et al., 2022) – is still enigmatic, though essential to elucidate on their occurrence. They have been commonly neglected in the literature, due to the difficulties in unambiguously demonstrating either their igneous nature or their crustal origin. However, in the last few years, the reported occurrences of anatectic carbonatites have exponentially increased (Su et al., 2024).

Here we present mesostructural, microstructural and geochemical evidence documenting the origin of anatectic carbonatites through in-situ partial melting of marly sediments in an orogenic setting, followed by immiscibility between silicate and carbonate liquids. The carbonate/silicate melt partition coefficients estimated for major elements are consistent with those experimentally determined for H_2O-bearing silica-rich potassic systems (Martin et al., 2013), with K, Al and Si concentrated in the silicate liquid and Na, Ca, Mn, Mg, Fe and Cl partitioned into the carbonate melt. These crustal-derived carbonate melts are relatively rich in silica (SiO_2 = 20-45 wt%), which makes them poorly reactive, and therefore highly mobile, potentially representing an efficient carrier of carbon within the crust.

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Yaxley G.M. et al. (2022) - Carbonatites: classification, sources, evolution, and emplacement. Ann. Rev. Earth Planet. Sci., 50, 261-293, https://doi.org/10.1146/annurev-earth-032320-104243.

New constraints on the emplacement, cooling and exhumation rate of the Monte Capanne Pluton (Elba Island, Northern Apennines)

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Keywords: emplacement, exhumation, thermo-rheological modelling.

The Monte Capanne pluton (Elba Island) is the largest exposed intrusive body in Tuscany and represents a key example of late Miocene magmatism within the Northern Apennines orogenic belt, being the westernmost and oldest granite, emplaced in the upper crust during the post-collisional extensional tectonics of inner Northern Apennines. Although previous studies have documented how the pluton was constructed (e.g. Farina et al., 2010; Barboni et al., 2015) and cooled (Boullin et al., 1994), the full history of emplacement and exhumation has yet to be fully determined. In this paper we combine new and existing determinations of the emplacement age and thermobarometry with apatite (U-Th)/He cooling ages to determine the exhumation history in order to constrain the interplay between extension, uplift and exhumation. We present the first attempt to implement fully coupled thermo-rheological simulations for the pluton using finite element methods, combining conductive and advective-convective heat transport. New U–Pb zircon ages confirm that the pluton was emplaced at 7.5±0.2 Ma during a period of crustal extension in the late Miocene. Thermodynamic modelling of contact metamorphism of metapelites suggests that it was emplaced at a depth of ~6.8 km. Apatite (U–Th)/He (AHe) ages of samples collected from the peak of the Monte Capanne pluton (1000 m above sea level) are 5.4±0.4 Ma while those collected close to the sea level provided a minimum value of 4.3±0.4 Ma. In our interpretation we assume that the AHe ages are indicative of the time, during exhumation, when the granite crossed the 80°C isotherm at a depth of 1-2 km, appropriate for thinned crust with elevated thermal gradient. To calculate a lower limit of the exhumation rate we use the maximum difference between the zircon U–Pb and the apatite AHe ages allowed by the uncertainties. The resulting estimates are 1.7 mm/yr (in a time interval of 2.7 Myr) for the granite sampled close to the peak of the Monte Capanne, and 1.4 mm/yr (in 3.8 Myr) for the granite sampled close to the sea level. Exhumation rates can be highly variable over time due to changes in crustal rheology, especially in zones close to the magma emplacement. Thermo-rheological modelling shows that convective heat transfer, compared to pure conductive scenarios, achieves better results with significantly higher exhumation rates dropping in short time intervals. The very fast exhumation may be due to the activity of an east-dipping extensional shear zone that is progressively unroofing the pluton, a consequence of Miocene extensional tectonics affecting the inner Northern Apennines and the opening of the northern Tyrrhenian basin.

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Carbon solubility in graphite-saturated haplogranitic melts: implications for the deep geological carbon cycle

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Keywords: carbon solubility, haplogranite, experimental petrology.

In the models of the geological carbon cycle, the contribution from crustal magmas is generally overlooked. However, organic matter that has been transformed to graphite through metamorphism could represent an important source of carbon in the lower crust, which can be re-mobilized during partial melting (Cesare et al., 2005). A COH fluid produced solely by dehydration in the presence of graphite will retain the H/O ratio of H_2O (H/O = 2) and thus maximize the H_2O activity and form of a ternary H_2O-CO_2-CH_4 mixture (Connolly & Cesare, 1993). Previous solubility studies have mainly considered oxidizing conditions (H/O < 2) and cannot be used to interpret graphitic systems, in which conditions are more reducing (Carvalho et al., 2023). Therefore, it is essential to obtain new solubility data for graphite-saturated silicate melt coexisting with a ternary H_2O-CO_2-CH_4 fluid.

In this study, solubility experiments were carried out in a single-stage piston cylinder apparatus at 5 to 10 kbar and in a temperature range of 800-1000°C. To simulate an anatectic melt formed in the mid to lower metasedimentary crust, a haplogranitic glass was synthesized, and the experimental charge was loaded with graphite and H_2O as the source for the COH fluid. To buffer the fluid composition at the condition H/O = 2 during the run, the double-capsule technique was utilized, and graphite and H_2O was added in the outer capsule. The speciation of the experimental fluid was analyzed ex-situ by a capsule-piercing quadrupole mass spectrometer (Tiraboschi et al., 2016). In all experiments H_2O was the major fluid component, in accordance with thermodynamic predictions, followed by variable amounts of CO_2 and CH_4. The relative amount of H_2O to carbonic species in the fluid changes with pressure and temperature, and the experiments cover a range of XH_2O_{fluid} = 0.67-0.99. The experimental glasses contain bubbles which have been analyzed by µ-Raman spectroscopy, revealing that they mainly consist of pure CH_4 or binary CH_4-CO_2 mixtures and graphite. Carbon contents of graphite- and fluid-saturated quenched glasses is up to 0.2 wt.% and is consistently lower than previous solubility experiments conducted at oxidizing conditions with binary H_2O-CO_2 fluids. Dissolved H_2O generally increases with pressure, and there is no visible temperature dependence. The presently used solubility models overestimate the carbon contents of these melts, especially at high pressure. These results emphasize the need to consider a ternary COH fluid in solubility models, due to the contrasting behavior of graphite and carbonate, since carbon solubility in silicate melts is strongly dependent on the composition of the coexisting fluid phase.

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Time-Temperature history of the Anzola gabbroic sill – insights from U–Pb geochronology (Val d'Ossola, Ivrea-Verbano Zone)

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Keywords: time-temperature path, U-Pb dating, Ivrea-Verbano Zone.

The thermal evolution and rheology of the lithosphere can be strongly affected by underplating of mafic magmas at the base of the continental crust or at higher structural levels. Mafic intrusions tend to facilitate continental extension by thermal weakening, but enhance crustal strength soon after they have cooled. Therefore, a detailed characterization of the temperature-time path of intrusive bodies is fundamental for reconstructing the tectono-metamorphic evolution of the middle and lower crust. Mafic magmatism in the middle-lower section of the Ivrea-Verbano Zone (IVZ) ranges from late Carboniferous to Jurassic (e.g., Denyszyn et al., 2018). The underplating of voluminous mafic intrusions, collectively known as the Mafic Complex, occurred during the early Permian and was accompanied by mostly coeval felsic magmatism and volcanism (e.g., Karakas et al., 2019). Minor mafic bodies emplaced at different crustal levels predate or postdate the Mafic Complex, making the evolution of the regional geotherm more complex. Here we present a preliminary geochronological data from the Anzola gabbroic sill (Val d'Ossola), emplaced at the transition from migmatites, towards SE, and granulites, towards NW. It is made of gabbroic rocks consisting of clinopyroxene and plagioclase with rare orthopyroxene. Amphibole is common while garnet is rare. Felsic segregations with a thickness ranging from a few cm up to 40 cm are also common. Gabbroic rocks are zircon-free and contain abundant apatite, conversely zircon and titanite are abundant within the felsic portions. The intrusion age of the Anzola gabbroic sill is still unknown. Hornblende Ar–Ar age of 247±7 Ma was obtained by Brodie et al. (1989) and interpreted as the cooling age of the sill intruded during the early Permian, coevally with the widespread lower crustal intrusives of the IVZ. Recent geochronological data revealed that the gabbroic rocks are bounded towards SE by a Triassic-Jurassic shear zone deforming mostly migmatites and minor mafic layers related to the Anzola sill (Corvò et al., 2023). In order to constrain the T-t path of the gabbroic sill we performed in situ U–Pb dating of zircon, garnet and apatite by LA-ICP-(MC)-MS. Preliminary results suggest an emplacement of the sill during early Permian, mostly coeval or slightly younger than the Mafic Complex (e.g., Karakas et al., 2019). Jurassic lower intercept ages obtained from apatite are indicative of either very slow cooling, or can reflect re-heating due to the hyperextension of the lithosphere as already documented by U–Pb data of rutile.

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Garnet, not always the archetypal cubic mineral: new crystallographic evidence from Cazadero (USA)

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Keywords: garnet, birefringence, symmetry reduction.

Garnet, being one of the most widespread minerals in the Earth, plays a crucial role for the investigation of many geological processes. Garnet occurs in several ultramafic to felsic rocks (e.g. mantle peridotites, granulites and metamorphic rocks) and can be a detrital component in sediments. It crystallizes in a wide range of *P-T* conditions, from the crust to the Transition Zone in the mantle, i.e. up to *P* ~25 GPa and *T* ~2000 °C (Baxter et al., 2013 and references therein). These features, along with the chemical variability and durability, make garnet an essential tool to determine the *P-T-t* history and the evolution of rocks.

Garnet is commonly defined as the archetypal cubic mineral, since it typically has *I*a-3*d* space group and isotropic optical properties under cross polarized light (Grew et al., 2013). Despite that, occurrences of birefringent garnets have been reported (Xu et al., 2023 and references therein). In some cases, the optical birefringence is explained as a consequence of symmetry reduction, from cubic to a lower one, possibly due to cation ordering in octahedral sites or to the presence of a significant hydrogarnet component in garnet structure (Xu et al., 2023 and reference therein).

Recent findings of sector-zoned birefringent and anhydrous garnets with almandine-grossular, $(Fe^{2+},Ca)_3Al_2(SiO_4)_3$, composition in blueschist- and greenschist-facies metamorphic rocks from several worldwide localities (e.g. Farinole, Cazadero, Jenner and eastern Italian Alps) suggested that optically anisotropic, probably not-cubic, garnets could be more common than generally assumed (Cesare et al., 2019). Cesare et al. (2019) proposed that these garnets could initially grow tetragonal in low-grade (T < 450°C) rocks, with possible implications about the use of this mineral as a marker for the processes occurring in such geological contexts. However, the causes of symmetry reduction (from cubic to tetragonal) and of the associated birefringence are not clear and a more detailed investigation is required.

Here, we report new crystallographic results on sector-zoned and anhydrous garnets with almandine-grossular composition in low-grade metamorphic metabasites from Cazadero (USA). Single-crystal X-ray diffraction data (n = 6) were collected on grains isolated from single birefringent sectors to determine the crystallographic features. In addition, EMPA flank method has been performed to detect the presence and amounts of Fe^{3+} in the studied garnets. Our results suggest that birefringence is caused by a symmetry reduction from cubic to orthorhombic, as proposed by Xu et al. (2023), connected with twinning and/or subsequent exsolution processes. In detail, we propose that birefringent garnets from Cazadero (re)crystallize in *I*2/*a*12/*d* space (unconventional setting for *Fddd*, pseudo-tetragonal cell with $c - a$ = -0.001 to -0.009 Å) and the reduction of symmetry is due to the ordering of Al-Fe^{3+} cations in the octahedral sites (Δ = 0.0021 to 0.0042 Å).

Baxter E.F. et al. (2013) - Garnet: Common mineral, uncommonly useful. Elements, 9(6), 415-419, https://doi.org/10.2113/gselements.9.6.415.

Cesare B. et al. (2019) - Garnet, the archetypal cubic mineral, grows tetragonal. Sci. Rep., 9(1), 14672, https://doi.org/10.1038/s41598-019-51214-9.

Grew E.S. et al. (2013) - Nomenclature of the garnet supergroup. Am. Mineral., 98(4), 785-811, https://doi.org/10.2138/am.2013.4201.

Xu H. et al. (2023) - Cation ordering, twinning, and pseudo-symmetry in silicate garnet: The study of a birefringent garnet with orthorhombic structure. Am. Mineral., 108(3), 572-583, https://doi.org/10.2138/am-2022-8455.

Garnet growth across the quartz-coesite transition in the Dora-Maira Massif: equilibrium vs. kinetics

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Keywords: quartz-coesite transition, Dora-Maira.

The thrilling discovery of elusive but definite occurrence of coesite in metapelites from the northern Dora-Maira Massif (in which it was so far unsuspected), offers a solid ground for (i) exploring the growth of garnet across the quartz-coesite transition in metapelites and (ii) assessing the main mineralogical changes, common to most metapelites.

This presentation will highlight several facets of this discovery:

The power of combining preserved growth zoning in garnet with the distribution of quartz/coesite inclusions and equilibrium thermodynamic modelling for predicting low temperature *HP/UHP* metamorphism in metapelites (Manzotti et al., 2022).

The contrasted behaviour of mono- and poly-cyclic metapelites with respect to Alpine garnet growth and silica-inclusion entrapment which emphasizes the role and variable extent of metastability in polycyclic rocks due to concurrent kinetic factors, such as effects of nucleation barrier, effective bulk composition, and fluid availability (Manzotti et al., 2025).

The first attempt to constrain the timing of burial and exhumation of the northern Dora-Maira Massif using U/Pb garnet petrochronology and the potential implications of the new garnet ages (Manzotti et al., 2025).

The areal-occurrence of coesite which on one hand considerably enlarges the rock volume affected by *UHP* metamorphism in the Dora-Maira Massif and on the other hand further highlights the major gap in the metamorphic structure of the Western Alps (i.e. the tectonic boundary between the lower Sanfront-Pinerolo and the higher *UHP* units; Manzotti et al., in press).

Manzotti et al. (2022) - A journey towards the forbidden zone: a new, cold, *UHP* unit in the Dora-Maira Massif (Western Alps). Contrib. Mineral. Petrol., 177, 59, https://doi.org/10.1007/s00410-022-01923-8.

Manzotti et al. (2025) - Protolith age, and timing of burial and exhumation of the *UHP* Chasteiran Unit (Dora-Maira Massif, Western Alps), constrained by zircon, garnet and rutile petrochronology. Lithos, 496-497, 107951, https://doi.org/10.1016/j.lithos.2025.107951.

Manzotti P. et al. (in press) - Garnet growth across the quartz-coesite transition in metapelites: equilibrium vs. kinetics. Eur. J. Mineral., 37.

Melt–residue disequilibrium microstructures in metacarbonate rocks: clues from thermodynamic modelling

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Keywords: anatectic carbonatites, coronas and symplectites, phase equilibrium modelling.

In the last decade, an increasing number of authors have suggested the possible generation of carbonatitic melts through partial melting of metacarbonate rocks (*e.g.* Su et al., 2024, and references therein) in the middle–lower crust of orogens subjected to high d*T*/d*P* ratios (Brown & Johnson, 2018). Despite growing interest, partial melting in nearly pure carbonate lithologies remains debated, primarily due to challenges in identifying and interpreting microstructures indicative of the former presence of melt. These difficulties have led to multiple, often debated, interpretations of similar microstructures, challenging the recognition of partial melting in metacarbonate rocks.

Here we present a collection of microstructures developed in high-grade calcitic and dolomitic marbles from various orogens, some of which have ambiguous interpretations—such as coronas formed at the expense of olivine (*e.g*. Su et al., 2022) or multiphase carbonate inclusions in high-grade minerals (*i.e*., olivine and spinel; Mizuochi et al., 2010). The peak mineral assemblages developed in the presence of melt in these lithologies, along with the associated retrograde disequilibrium microstructures, have been investigated through phase equilibrium thermodynamic modelling. *T*–*X*(CO_2) and μMgO–*X*(CO_2) pseudosections allowed us to constrain temperature and fluid composition, which, together with microdomain effects, affected the development of the peak mineral assemblages described in the literature. The sequential order of coronas and symplectites development around olivine, a topic of considerable debate (*e.g.* Mizuochi et al., 2010; Su et al., 2022), was modelled through multiple μMgO–μCaO grids at varying *P*–*T* conditions. Using this approach, we argue that a specific range of fluid and bulk-rock composition is likely required to enable partial melting in nearly pure calcitic and dolomitic marbles under amphibolite- to granulite-facies conditions along an orogenic P–T path.

Brown M. & Johnson T. (2018) - Secular change in metamorphism and the onset of global plate tectonics. Am. Mineral., 103, 181-196, doi.org/10.2138/am-2018-6166.

Mizuochi H. et al. (2010) - Exsolution of dolomite and application of calcite–dolomite solvus geothermometry in high-grade marbles: an example from Skallevikshalsen, East Antarctica. J. Metam. Geol., 28, 509-526, https://doi.org/10.1111/j.1525-1314.2010.00877.x.

Su B.-X. et al. (2022) - Element partitioning and Li-O Isotope Fractionation Between Silicate Minerals and Crustal-Derived Carbonatites and Their Implications. J. Geophys. Res.: Solid Earth, 127, e2022JB024563, https://doi.org/doi.org/10.1029/2022JB024563.

Su B.-X. et al. (2024) - Crustal-derived versus mantle-derived carbonatites. Lithos, 488-489, 107826, https://doi.org/10.1016/j.lithos.2024.107826.

Multiscale modelling of stress at solid-fluid interfaces: implications for the interplay of deformation and mineral reactions

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Keywords: mineral equilibria, stress, deformations.

The interpretation of mineral equilibria and reactions in rocks assumes uniform hydrostatic pressure across all phases. However, due to deformation, this hydrostatic condition is often not satisfied in the lithosphere, where stress gradients and non-hydrostatic stresses develop even in the presence of fluids. This challenges the reliability of existing hydrostatic thermodynamic models, and currently, there is no accepted theory for evaluating the thermodynamic effect of non-hydrostatic stress on reactions (e.g. Hobbs & Ord, 2016; Wheeler, 2020).

Large-system Molecular Dynamics (MD) simulations with more than one million atoms allow the investigation of equilibria in deforming systems, bridging atomic-level processes and continuum deformation. With MD, a system of solid grains and fluid under deformation can be studied at the atomic scale. This method does not require assuming a specific thermodynamic potential, making it a robust test for existing thermodynamic theories (Mazzucchelli et al., 2024). MD simulations enable monitoring of dissolution and precipitation until equilibrium is reached. We also show how the Cauchy stress can be computed directly from interatomic forces with a spatial resolution on the order of one unit-cell, by coupling a continuum mesh to the atomistic simulation. This allows accurate resolution of stress gradients, concentrations, and discontinuities at interfaces, even in complex geometries. The stress obtained matches precisely the stress from analytical and numerical (finite element) models of continuum mechanics for the same geometry and deformation, providing a direct link between atomistic and continuum scales.

By adopting this approach, we test the predictions of Gibbs (1876) concerning the equilibrium of a single-component non-hydrostatically stressed solid with a fluid. Our findings confirm that a solid under non-hydrostatic stress can be equilibrated with its pure fluid. However, as predicted by Gibbs, increasing non-hydrostatic stress leads to system instability, ultimately resulting in the precipitation of a quasi-hydrostatically stressed crystalline layer on the surface of the highly stressed crystal. During crystallization, the total stress balance is preserved until the newly formed system, consisting of a high-stress solid, a low-stress solid layer and the fluid, reaches a stable equilibrium. At the final equilibrium, only the low-stress solid layer is in contact with the fluid, bringing the equilibrium fluid pressure close to the value expected for equilibrium under homogeneous hydrostatic conditions. While our results qualitatively and quantitatively agree with previous thermodynamic theories for deformed systems and experimental observations, they cannot be predicted by the existing theories used to interpret reactions in deformed geological systems.

Gibbs J.W. (1876) - On the Equilibrium of Heterogeneous Substances - Part II. Trans. Connecticut Acad. Arts Sci., 3, 108-248.

Hobbs B.E. & Ord A. (2016) - Does non-hydrostatic stress influence the equilibrium of metamorphic reactions? Earth Sci. Rev., 163, 190-233.

Mazzucchelli M.L. et al. (2024) - Fluid-mineral Equilibrium Under Nonhydrostatic Stress: Insight From Molecular Dynamics. Am. J. Sci., 324, 2, https://doi.org/10.2475/001c.92881-

Wheeler J. (2020) - A unifying basis for the interplay of stress and chemical processes in the Earth: support from diverse experiments. Contrib. Mineral. Petrol., 175, 116.

Insights into metamorphic processes *via* joint chemical-mechanical inversion techniques

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Keywords: metamorphic, sole, inversion.

Metamorphic rocks record complex dynamic histories in which temperature (T) and pressure (P) evolve over time (t). Discrete parts of these histories can be constrained with geochronological techniques, equilibrium thermodynamics, or mechanical methods such as elastic barometry. These techniques enable the determination of mineral entrapment conditions, the (near-)peak of metamorphism or the duration of exhumation. Furthermore, they can serve as important constraints to various inversion methods. In this work, we focused on the metamorphic sole of the Pindos ophiolite in northwestern Greece. Based on previously obtained geochronological and thermobarometric data, we derive effective cooling rates through a combination of inversion techniques. Specifically, we employed a non-linear, multicomponent diffusion model to reproduce observed compositional gradients in garnet by finding an optimal cooling rate relevant to the near-peak conditions. In addition, $^{40}Ar/^{39}Ar$ ages of muscovite from a metapelite and hornblende from an amphibole of the Pindos metamorphic sole were fit using a similar diffusion approach to obtain an effective cooling rate. Finally, these results can be corroborated using a visco-elasto-plastic numerical model to solve the host-inclusion (Lamé) problem in spherical coordinates. This model accounts for the viscous relaxation of the quartz-in-garnet system and can also be utilized to estimate an effective cooling rate. We demonstrate that integrating chemical and mechanical inversion techniques with petrological data is advantageous for elucidating the complex evolution of metamorphic rocks.

Metamorphic devolatilisation inhibits mercury (Hg) recycling into the Earth's mantle

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Keywords: mercury (Hg) loss, subduction zone, negligile deep mercury cycle

The recycling of mercury (Hg) into the Earth's mantle and its re-emission into the atmosphere by arc magmatism has been recently proposed based on the similar positive Δ^{199}Hg values (0 to 0.4‰) between seawater, marine sediments, and magmatic rocks (e.g., Yin et al., 2024). However, by reviewing the Hg concentrations in ophiolite and orogenic peridotites, eclogite and peridotite xenoliths, different mantle-derived mafic-ultramafic (Mg# [Mg/(Mg + Fe) mol%] ≥60) magmas, and in rocks from variably metamorphosed terrains consisting of lithologies similar to those subducting nowadays, we propose and alternative scenario. Sedimentary and igneous protoliths in metamorphic terrains have similar high Hg concentrations (80-100 ng/g), but exhibit a significant Hg loss (~97%) before reaching high-grade metamorphism (P ~1.0 GPa; T > 500 °C). Intriguingly, based on Hg LA-ICP-MS analyses in sulphide inclusions in diamonds from a ~1.85-Ga-old eclogite xenolith from the Central Slave Craton, the reconstructed bulk eclogite had ≤1 ng/g of Hg (Aulbach et al., 2012).

Peridotites and mantle-derived magmas share similar Hg contents, from ~0.2 to ~20 ng/g. Nonetheless, these concentrations do not allow further discussions because they were obtained with thermal decomposition atomic absorption spectroscopy instruments, which are inaccurate and imprecise when used to analyse crystalline rocks having Hg ≤10 ng/g, and are unable to release all Hg from mafic-ultramafic rocks (Narduzzi et al., 2025). When data from metamorphic rocks are plotted in a P-T-Hg diagram together with modern-day P-T subduction paths, Hg recycling into the mantle appears negligible because it is almost lost from any subducting lithology before sub-arc depths (P ≥2.5 GPa; T ≥700 °C) due to metamorphic devolatilisation. A similar conclusion is proposed for the Archean when the estimated P-T subduction paths at ~2.5 and ~4.0 Ga and the bulk Hg concentration of the Paleoproterozoic eclogite are also considered. The present review showcases a paradox in the geochemical cycle of Hg. While Hg isotopes indicate the recycling of Hg into the mantle, the elemental behaviour of Hg at subduction zones would suggest that ≤3 ng/g are transferred to the sub-arc mantle. If further accurate and precise analyses confirm the negligible recycling of Hg into the mantle, this might have significant implications for the origin of Hg degassed from arc volcanoes and the cycle of Hg in the deep Earth.

Aulbach S. et al. (2012) - Chalcophile and siderophile elements in sulphide inclusions in eclogitic diamonds and metal cycling in a Paleoproterozoic subduction zone. Geochim. Cosmochim. Acta, 93, 278-299, http://dx.doi.org/10.1016/j.gca.2012.04.027.

Narduzzi F. et al. (2025) - Strengths and weaknesses of the analytical techniques used for measuring low mercury mass fractions (< 10 ng g^{-1}) in crystalline rocks: Direct Mercury Analyser versus Cold Vapour-Atomic Fluorescence Spectroscopy. Geostand. Geoanal. Res., 49(2), 295-314, https://doi.org/10.1111/ggr.12606.

Yin R. et al. (2024) - Linking the mercury biogeochemical cycle to the deep mercury cycle: A mercury isotope perspective. Chem. Geol., 654, 122063, https://doi.org/10.1016/j.chemgeo.2024.122063.

Onset of hydration in the gabbroic oceanic core complex of Atlantis Bank (Southwest Indian Ridge)

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Keywords: amphiboles, lower oceanic crust hydration, fluid-melt interaction.

The role of ductile and brittle deformation in transporting seawater-derived fluids at depth, the depth reached by these fluids, and how these fluids interact with the deepest parts of the lower oceanic crust are fundamentally unknown. To fill this gap, we present a petrological and geochemical investigation of brown amphibole veins and brown amphibole mylonites collected from IODP Hole U1473A from the gabbroic oceanic core complex of Atlantis Bank from the Southwest Indian Ridge. Amphibole veins and amphibole mylonites were inferred to have formed during the early stages of the exhumation evolution, at the ductile-brittle transition, and are concentrated in the top ~200 m of the gabbroic section (MacLeod et al., 2017).

Amphibole veins typically host minor amounts of plagioclase, and the amphibole mylonites consist of amphibole, plagioclase, and accessory Fe-Ti-oxide phases. Amphibole in veins and mylonites overall has 8.1-9.1 wt% Al_2O_3 and 1.5-2.0 wt% TiO_2 and contains relatively high concentrations of Cl (0.2-0.5 wt.%) and B (1.5-3.3 ppm). The coexisting plagioclase has 30-47 mol% anorthite, 1.4-3.8 ppm of B, and a Sr isotopic signature of 0.7027 ± 0.0001, overlapping that of Atlantic Bank basalts and host gabbros (Kempton et al., 1991; Marschall et al., 2017). The amphibole-plagioclase pairs remarkably record high crystallisation temperatures, which cluster at 770-860 °C.

Vein and mylonitic amphiboles have lower Mg# and higher Ti, Mn, REE, and HFSE concentrations than the enclosing gabbros. Such chemical differences argue against the formation of amphibole veins and amphibole mylonites through the interaction of solid-state gabbros with seawater-derived fluids and suggest the involvement of a melt component. We envision that the ductile-brittle transition was associated with the formation of a fracture network in the carapace of the exhuming gabbroic section, which aided the migration of seawater-derived fluids at depth and enabled the interaction with variably evolved rising melts. Boron isotope analyses of amphibole are currently in progress to constrain the process of fluid-melt interaction and help disentangle the downward pathway of seawater.

Kempton P.D. et al. (1991) - Geochemistry and isotopic composition of gabbros from layer 3 of the Indian Oceanic Crust, Hole 735B. Proc. Ocean Drill. Progr., 118, 127-143, https://doi.org/10.2973/odp.proc.sr.118.118.1991.

MacLeod C.J. et al. (2017) - Southwest Indian Ridge Lower Crust and Moho. Proc. Int. Ocean Discov. Progr., 360, https://doi.org/10.14379/iodp.proc.360.103.2017.

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Garnet flat habit and honeycomb texture are controlled by nutrient availability during Barrovian metamorphic reactions

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Keywords: orientation analysis, trace elements, thermodynamic modelling.

In orogenic settings, elongated and flattened garnet textures are reported mainly from high-temperature or high-pressure terranes (e.g., Hawkins et al., 2007; Festa et al., 2024), whereas only a few studies investigate them at subsolidus Barrovian metamorphic conditions (e.g., George & Gaidies, 2020). Skeletal and poikiloblastic garnet textures are more common, although strong fishnet/honeycomb textures have been rarely reported and investigated (Hawkins et al., 2007). Different processes have been invoked to explain the elongated shapes and skeletal textures. Specifically, post-growth deformation, coalescence of garnet crystals and/or epitaxial growth on pre-existing minerals have been interpreted as the main processes controlling the elongated habit, whereas the presence of an intergranular fluid is the main constraint proposed for honeycomb garnet. The presence of a spaced bending with quartz-rich layers is also a controlling factor.

In this study, we integrate microstructural and microchemical analyses using X-ray μ-CT, LA-ICP-MS maps and EBSD maps with forward thermodynamic modelling on a garnet-bearing quartz-rich micaschist from the upper portions of the Lesser Himalayan Sequence of eastern Nepal Himalaya, which reached amphibolite-facies conditions. The studied sample shows a spaced banding defined by quartz-rich and muscovite-rich layers. Garnet porphyroblasts are mainly developed along or near the muscovite-rich layers and mainly consist of a massive internal portion and a skeletal rim. X-ray μ-CT of the sample highlights garnet crystals with a flat, oblate habit oriented parallel to the main foliation. EBSD maps on garnet crystals show homogeneous grains without internal strain, both in the massive and skeletal portions. This evidence allows the exclusion of either post-growth deformation or coalescence as the main processes controlling the development of the flat habit. LA-ICP-MS maps show concentric prograde major-elements zoning and Reyleigh fractionation of heavy rare earth elements, not displaying any oscillatory zoning or concentrated rims. Dissolution-reprecipitation is therefore also excluded as the main mechanism. Forward thermodynamic modelling helps investigate the metamorphic reaction(s) producing garnet, and the role of nutrient availability during its growth.

Festa V. et al. (2024) - Garnet coalescence clogs melt extraction channels in migmatite. Lithos, 472-473, 107581, https://doi.org/10.1016/j.lithos.2024.107581.

George F.R. & Gaidies F. (2020) - Simultaneous operation of opposing reaction mechanisms: The influence of matrix heterogeneity on post-kinematic garnet crystallization in an inverted metamorphic sequence. J. Metamorp. Geol., 38, 743-769, https://doi.org/10.1111/jmg.12539.

Hawkins A.T. et al. (2007) - Origin and mechanical significance of honeycomb garnet in high-pressure metasedimentary rocks from the Tauern Window, Eastern Alps. J. Metamorp. Geol., 25, 565-583, https://doi.org/10.1111/j.1525-1314.2007.00714.x.

The contribution of the petrological iterative approach in unveiling hidden UH*P* evidence

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Keywords: Bingo-Antidote, UHP metamorphism, thermodynamic modelling.

Recent advances in petrological and image analysis approaches open new research directions, leading to an increasingly statistically oriented thermodynamic forward modelling and more accurate subsequent interpretations. Isopleth thermobarometry, i.e., comparing compositional isopleths computed from forward thermodynamic models with measured mineral compositions, is commonly applied to retrieve the pressure (*P*) and temperature (*T*) conditions of equilibration (e.g., Groppo, 2025, and references therein). However, thermobarometric estimates are still limited by the lack of quantitative constraints on their uncertainties, necessary to evaluate the reliability of the obtained results. To fill this gap, Bingo-Antidote (Duesterhoeft & Lanari, 2020), an XMapTools add-on, applies an iterative routine to statistically quantify the goodness of fit between the model and the natural sample.

This work applies the Bingo-Antidote approach to a chloritoid–garnet-bearing micaschist from the southern Dora-Maira Massif (Western Alps), which is the archetypal location for the establishment of the concept of ultra-high pressure (UH*P*) metamorphism, and where new UH*P* localities are continuously discovered (Manzotti et al., 2022; Groppo et al., 2025). Although collected from a high-pressure unit, calculations highlighted a good match between the observation and the model at conditions that overlay the quartz-coesite polymorphic reaction. This statistical information called for targeted investigations, which ultimately led to the recognition of coesite inclusions in the garnet domain modelled to be equilibrated at such conditions, pinpointing the pressure peak at UH*P* conditions. Our results corroborate the importance of Bingo-Antidote as a straightforward, reliable and fast tool for quantitatively defining the metamorphic conditions experienced by a selected mineral assemblage, and the associated statistical error. Additionally, as new occurrences of UH*P* evidence are emerging, our results call for re-examining the distribution of UH*P* metamorphism in the Dora Maira Massif, possibly applying Bingo-Antidote as a screening for further targeted research.

Duesterhoeft E. & Lanari P. (2020) - Iterative thermodynamic modelling—Part 1: A theoretical scoring technique and a computer program (Bingo-Antidote). J. Metamorph. Geol., 38, 527-551, https://doi.org/10.1111/jmg.12538.

Groppo C. (2025) - P–T–X conditions of metamorphic systems. Treatise on Geochemistry, 3rd e. 2, 411-446, https://doi.org/10.1016/B978-0-323-99762-1.00001-2.

Groppo C. et al. (2025) - A New UHP-HP Tectono-Metamorphic Architecture for the Southern Dora-Maira Massif Nappe Stack (Western Alps) Based on Petrological and Microstructural Evidence. J. Metamorph. Geol., 43(4), 359-383, https://doi.org/10.1111/jmg.12812.

Manzotti P. et al. (2022) - A journey towards the forbidden zone: a new cold UHP unit in the Dora-Maira Massif (Western Alps). Contrib. Mineral. Petrol., 177, 59, https://doi.org/10.1007/s00410-022-01923-8.

Tectono-metamorphic history of a Variscan lower crustal cross-section (Val d'Ossola, Ivrea-Verbano Zone)

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Keywords: anatexis, geochronology, metamorphism.

The lower continental crust is arguably one of the most enigmatic portions of our planet: its inaccessibility, large geochemical variability, multi-stage evolution, and complex mineral records make it challenging to decipher the various crust-forming processes. Yet, the lower continental crust holds vital clues to deep Earth processes, such as element cycling and storage, and large-scale geodynamics.

This contribution presents a comprehensive geochemical and petrochronological characterization of an archetypical lower crustal section. In the northern sector of the Ivrea Verbano Zone, along Val d'Ossola, a ca. 10 km-thick former lower crustal terrane is now exposed at the Earth's surface. This section, bordered by major tectonic lineaments, preserves a metamorphic field gradient from amphibolite- to granulite-facies conditions. The abundances of the main lithologies were reconstructed based on fieldwork, and approximately 80 field samples were studied, acquiring a large geochemical and petrological dataset. This dataset will play a crucial role for the upscaling of the results from the ICDP-DIVE (Drilling the Ivrea Verbano zonE, http://www.dive2ivrea.org/) boreholes, which were recently drilled within the sequence. Bulk rock data permits to characterize the lithologies (felsic sediments, amphibolites, calcsilicates mafic granulites, marbles and ultramafics) and identify lithological subgroups. The mineral chemistry of the main rock-forming minerals, including garnet and feldspars, exhibits systematic changes with metamorphic grade and across different lithologies, providing a further tool for a more robust classification of the rock types.

Various geothermobarometers were applied to constrain the pressure and temperature conditions recorded at different depths. In particular, the robustness of the Zr-in-garnet thermometer was assessed and directly compared with the Zr-in-rutile thermometer, proving to be a valuable tool to constrain peak temperatures in high-grade felsic rocks. Geothermometric results demonstrate that the sequence records an increase in metamorphic grade from ca. 650 °C to ca. 950 °C. However, the geothermometric results, further supported by field observations, indicate that the progressive increase in temperature conditions is interrupted by a metamorphic jump of ca. 50-100 °C, across the Anzola Shear Zone, a major tectonic discontinuity. The P-T investigation was coupled with U-Pb dating of zircon, in order to investigate the temperature-time-melting history. The felsic and mafic rocks of the sequence record metamorphic ages ranging from 280±4 to 260 ± 4 Ma. The oldest age, 280±4 Ma, is obtained from zircon of the amphibolites and it is interpreted to reflect the prograde-to-peak history of the lower crustal terrane. The ages from the mobilized anatectic leucosomes mostly occur at 260±4 Ma, reflecting zircon crystallization during cooling and providing a lower limit to the anatectic history of the Ivrea lower crust.

The Role of high-pressure Antiskarn Process in the formation of crustal Ca-carbonatites of Ivrea-Verbano Zone (Northern Italy)

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Keywords: crustal carbonatites, antiskarn process, Ivrea-Verbano Zone (IVZ).

The Italian western Alpine chain's Ivrea-Verbano Zone (IVZ) is an exhumed portion of the lower continental crust formed during Permian lithospheric extension (Quick et al., 2003). Here, carbonatites have been recently reported by Galli et al. (2019). The focus of the study was the characterisation of a carbonatite sampled in outcrop in the Rimella area (Mastallone Valley). The carbonatite occurs embedded in mafic granulites and show fluidal textures, liquidus-phase minerals, presence of mafic xenoliths, and reaction textures. This carbonatite is a breccia-like rock characterized by a fine-grained and cream-colored matrix with a subtle pinkish halo, and the xenoliths are several centimetres in length. The matrix is calcite-dominated with accessory apatite, pyrite, and thorite. The xenoliths are surrounded by reaction coronae of anorthite, Ca-rich clinopyroxene, sphene, rutile, ilmenite and zircon. The interaction between the carbonatitic melt and the xenoliths suggests an antiskarn process in which CO_2-rich fluids mobilise Ti, Zr and rare earth elements, facilitating their incorporation into reaction mineral phases (REE; Hynes, 1980).

Thermo-barometric estimation of chemical variations in pyroxene indicates that the transition from primary Ti-rich clinopyroxene to reaction igneous Ca-rich clinopyroxene occurred at temperatures between 660 and 1300 °C and pressures of 10–14 kbar during xenolith-carbonatite interaction. These conditions are typical of a crustal environment where the carbonatite melts were formed. In addition, the IVZ carbonatites have REE concentrations that are two orders of magnitude lower than mantle-derived carbonatites, but consistent with worldwide crustal carbonatites.

Igneous textures, mineralogy, reaction features and REE contents support the hypothesis that IVZ carbonatites originated within the crust, from melting of marbles. This is consistent with the marble melting and secondary metasomatism model, but inconsistent with mantle genesis of carbonatites (Su et al., 2024).

Galli A. et al. (2019) - Jurassic carbonatite and alkaline magmatism in the Ivrea zone (European Alps) related to the breakup of Pangea. Geology, 47(3), 199-202.

Hynes A. (1980) - Carbonatization and mobility of Ti, Y, and Zr in Ascot Formation metabasalts, SE Quebec. Contrib. Mineral. Petrol., 75, 79-87.

Quick J.E. et al. (2002) - Geologic map of the southern Ivrea-Verbano Zone, northwestern Italy. USGS, https://pubs.usgs.gov/imap/2776/report.pdf.

Su B.X. et al. (2024) - Crustal-derived versus mantle-derived carbonatites. Lithos, 488, 107826.

Exploring natural analogues for CO_2 storage: listvenites along regional fault zones in the Zermatt-Saas Unit (Western Alps, Italy)

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Keywords: carbonated serpentinites, carbon capture and storage, X-ray powder diffraction.

In the last decades many studies focussed on carbon capture and storage (CCS) to find a possible remedy to reduce the increase of anthropogenic carbon dioxide (CO_2). In geological reservoirs, CO_2 can be trapped by mineral carbonation which plays a crucial role in CCS, being almost irreversible, involving the chemical reaction in aqueous environment between CO_2 and Mg- and/or Ca-rich minerals, where CO_2 is converted into solid carbonates. In nature, listvenite, a rock mainly composed of Mg-Ca-carbonates, quartz and Cr-mica (fuchsite), documents natural CO_2 sequestration. Indeed, listvenites are the result of the extensive alteration of ultramafic rocks by CO_2-bearing fluids, which involved the substitution of olivine, pyroxene and serpentine by Ca- and Mg-carbonates. To date, very little is known about the kinetics and rate of this reaction, spanning from weeks (serpentinites) to thousands of years (peridotites). First listvenitic fault breccias in mantle serpentinites of the Western Alps were reported in the Aosta valley from the Rocca di Verra-Breithorn massif and the abandoned quarry of Sizan, both in the Ayas valley and the Zermatt-Saas Zone (Dal Piaz & Omenetto, 1978). We studied carbonated serpentinites from the Zermatt-Saas Zone (Corno del Camoscio, Western Alps, Italy; Dal Piaz et al., 2010) which underwent fluid-mediated natural carbonation. Hydrothermal carbonation is spatially associated to Oligo-Miocenic brittle faults of the Aosta-Ranzola system (Bistacchi et al., 2001). Field structural study identified two main strike-slip fault sets (N-S and NW-SE striking) controlling fluid flow, with voluminous carbonation observed mainly along the NW-SE-striking set. We collected structurally-controlled samples along a reaction front from serpentinite to listvenite close to a major fault zone, aiming to relate the CO_2-rich fluid/rock interaction with mega and meso-structures. The petrographic study, along with SEM-EDS maps, microprobe chemical analyses and X-ray powder diffraction (XRPD) have allowed us to identify the phase assemblages along the reaction front: from a Mg-silicate rich serpentinite, with minor quartz, magnesite and dolomite to a fully carbonated listvenite composed of quartz, fuchsite and Mg-carbonates, with relict brucite. Interestingly, microstructures in the samples collected close to the serpentinite show carbonates pre- and syn-kinematic to the ductile fabrics. Thus, our study identified a more complex history of fluid-mediated carbonation, defined by a two-phase process: the first carbonation occurring during ductile deformation, and the second one during brittle faulting. Qualitative and quantitative XRPD data enabled us to calculate a mass balance to model the rate of reaction and the composition of the original fluids. Preliminary results indicate a structural control on the fluid drainage and the role of brucite to dominate the carbonation reaction, as reported by experimental results of Campione et al. (2024).

Bistacchi A. et al. (2001) - The Aosta–Ranzola extensional fault system and Oligocene–Present evolution of the Austroalpine–Penninic wedge in the northwestern Alps. Int. J. Earth Sci., 90, 654-667, https://doi.org/10.1007/s005310000178.

Campione M. et al. (2024) - Microwave-driven carbonation of brucite. Journal of CO_2 Utilization, 80, 102700, https://doi.org/10.1016/j.jcou.2024.102700.

Dal Piaz G.V. et al. (2010) - Geologia. In: Leonoris C. (Ed): Percorso Geologico-Pedologico di Cimalegna. Parco Naturale Alta Valsesia, 25 p.

Dal Piaz G.V. & Omenetto P. (1978) - Brevi note su alcune mineralizzazioni della Falda Piemontese in Valle d'Aosta. Ofioliti, 3, 161-176.

Microstructural study of the graphitic schists "Furtschaglschiefer" of Passo di Vizze (SW Tauern Window, Eastern Alps, Italy)

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Keywords: biotite, boudinage, graphite

This study is aimed at the microstructural analysis and at the reconstruction of the deformation history of some peculiar microboudinaged biotite porphyroblasts from the SW Tauern Window (Passo di Vizze, Italy). The studied schists (Furtschaglschiefer *Auct*.) derive from a pelitic protolith in the SW Tauern Window that has been metamorphosed under upper greenschists to lower amphibolite facies conditions during the Alpine orogenesis.

The principal components of the schist are: quartz, plagioclase, garnet, biotite, ilmenite, muscovite, graphite ± chlorite ± epidote ± staurolite, of which biotite, garnet and ilmenite show porphyroblastic behaviour. The fabric analysis was performed using 2D data collected during detailed petrographic analysis on oriented thin sections (strain quantification, aspect ratio and analysis) and using 3D data collected with Micro X-ray Computed Tomography (µXCT, shape and orientation analysis).

Biotite appears in many different microstructural settings, but it is possible to define three main types: the "foliation-perpendicular" microboudinaged biotites (type I), the fanned *mica-fish* biotites (type II) and the foliation-parallel elongated biotites (type III). The microboudinaged biotites are the coarser in size (up to 1 cm) and typically show alternating graphite-rich sectors formed by thin (µm-scale) chlorite-biotite intergrowth separated by clean biotite. Quartz necks can be found at the highest total strains (up to 176%). Type I biotite sectors, as well as biotite cleavage planes, are perpendicular to the foliation while the graphite inclusions are parallel to it. Fanned biotites and elongated biotites are showing oblique and foliation-parallel cleavages, respectively. Garnet is euhedral with sizes up to 1 cm and shows non-cubic symmetry (Cesare et al., 2019). It is characterized by symmetric strain shadows and hourglass shaped graphitic inclusions. Ilmenite is characterized by coin-shaped grains with symmetric chlorite-quartz strain shadow in clear textural equilibrium. Rendering of the rock volumes and the 3D data of the different shape axes showed preferred orientation of all types of biotite and iso-orientation of ilmenite porphyroblasts.

Our analysis revealed that microboudinage coupled with limited rotation under pure shear deformation of the porphyroblast are the principal deformation mechanisms for type I and II biotites. Adding to the deformational history of these schists, their complex P-T-t history has also been characterized via thermodynamic modelling, RSCM thermometry, QuiG barometry and in-situ U-Pb garnet geochronology.

Cesare B. et al. (2019) - Garnet, the archetypal cubic mineral, grows tetragonal. Sci. Rep., 9(1), 14672, https://doi.org/10.1038/s41598-019-51214-9.

A novel analytical method for $\delta^{13}C$ determination of CO_2-bearing fluids in petrological experiments: a tool for tracking carbon in metamorphic processes

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Keywords: stable carbon isotopes, CO_2, experiments.

Fluids play a critical role in metamorphic and geodynamic processes, governing mass transfer, redox conditions, and isotopic exchange in the deep Earth. Among these, CO_2-bearing COH fluids are key carriers of carbon during subduction and crustal recycling. Their stable isotopic signature ($\delta^{13}C$) is essential to understand and quantify the exchanges between geological reservoirs. However, measuring $\delta^{13}C$ in these fluids at natural isotopic abundance remains analytically challenging due to the small fluid volumes typically produced in high-pressure petrological experiments.

We present a novel protocol that integrates quadrupole mass spectrometry (QMS) with isotope ratio mass spectrometry (IRMS) for $\delta^{13}C$ analysis of CO_2 in experimentally produced COH fluids. This technique, recently published (Toffolo et al., 2025), employs a capsule-piercing device to recover the fluid phase and transfer it into IRMS-compatible vials without inducing isotopic fractionation.

The method was first validated through thermal decomposition of anhydrous oxalic acid. The resulting fluids, dominated by CO_2 and H_2O, showed highly reproducible $\delta^{13}C$ values (±1‰). Then, the application to redox-buffered piston-cylinder experiments at 3 GPa and 700 °C, where green microalgae were used as an organic carbon source to simulate mobilization from subducted sediments, yielded $\delta^{13}C$ consistent with closed-system CO_2-graphite fractionation.

This approach allows direct quantification of isotopic fractionation between CO_2 either carbonates or carbonaceous materials under HP–HT conditions, providing a powerful tool to track carbon behavior during metamorphism. Its integration into experimental workflows enables more realistic simulations of natural systems, bridging the gap between laboratory results and crustal-scale processes. Future extensions include $\delta^{13}C$ measurements of CH_4, opening perspectives for reduced fluid systems relevant to graphite–diamond formation and deep carbon cycling.

Toffolo L. et al. (2025) - A reliable analytical procedure to determine the carbon isotopic signature of CO_2-bearing COH fluids generated in petrological experiments. Eur. J. Mineral., 37, 25-37.

Possibility of obtaining bactericidal fillers for paper production and filter materials for water purification based on natural phillipsites of Georgia

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Keywords: zeolite, phillipsite, bacteriostatic activity.

Zeolites are microporous crystalline aluminosilicates used as molecular sieves, adsorbents, ion exchangers and catalysts in industry, agriculture, environment protection and other fields. Metal-containing zeolite adsorbents and ion exchangers endowed with bacteriostatic activity are promising for medical use, the production of paper and polymer materials, as well as for environmental protection, in particular, for purifying water from microorganisms and inorganic/organic pollutants. Purpose of our study was to use phillipsites of the Georgian deposits for preparation of silver-, copper- and zinc-containing forms.

Phillipsite samples were collected at the lower Tsinubani plot of the Akhaltsikhe deposit and at the Shukhuti manifestation; the content of the zeolite phase in these samples is quite high – 70 and 80 %, and the main impurity of the sample from Shukhuti is heulandite, the most common zeolite in Nature, so this sample seems to be a more effective adsorbent and ion exchanger. Two methods of carrying out ion-exchange reactions were used: "solid" (preparation of a finely dispersed mixtures of zeolite with salt, followed by washing) (Tsitsishvili et al., 2022) and "liquid" (treatment of zeolite with salt solution) (Tsitsishvili et al., 2020). In both cases, a fairly high content of biologically active metals was achieved.

The X-ray diffraction patterns and Fourier transform infrared spectra confirm the preservation of the crystal structure of zeolites with the introduction of silver, copper and zinc ions. The adsorption of water molecules passing through all three "entrance windows" into phillipsite channels shows a decrease in the free volume of micropores with the introduction of large ions, while the total pore volume does not change. Adsorption-desorption isotherms of nitrogen molecules passing through only one "entrance window" into channels show the presence of a developed system of mesopores that ensure the immobilization of large molecules and ions.

Bacteriostatic properties of zeolite samples were determined by the disk diffusion (Kirby-Bauer) method using the cultures of gram-negative bacteria *Escherichia coli* and *Salmonella enteritidis*, gram-positive bacteria *Staphylococcus aureus* and *Bacillus subtilis*, fungal pathogenic yeast *Candida albican*s and a fungus *Aspergillus niger*. The results of the Kirby-Bauer test show that no antibacterial action was observed for the original phillipsite, activity decreases in the Ag>Cu>Zn series against E. coli, copper and silver forms are active against staphylococcus, copper and zinc forms are most active against hay bacillus; as for fungi, the copper form is not active, the growth of Candida is most inhibited by the silver form, the growth of the black fungus by the zinc form.

In conclusion, the following can be stated: natural phillipsites are good carriers of bioactive metals, and their use is possible both for water purification and disinfection, and as fillers in the production of polymeric materials, paper and cardboard.

Tsitsishvili V. et al. (2022) - Bactericidal metal-containing zeolites. Chem. Phys. Technol. Surf., 13(4), 489-497.

Tsitsishvili V. et al. (2020) - Properties of Bactericidal Adsorbents Prepared from Georgian Natural Analcime and Phillipsite. Bull. Georgian Nat. Acad. Sci., 14(4), 25-33.

Zn-containing zeolite as a filler to produce paper with antimicrobial properties

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Keywords: zeolite, clinoptilolite, bacteriostatic activity.

The work aims at developing sustainable packaging paper endowed with enhanced antimicrobial properties and having a modified waterproof surface. It is known, that changing the properties of paper and cardboard, including providing them with antimicrobial properties, is possible with the help of special fillers, among which zeolites containing biologically active metals (Ag, Cu, Zn, etc.) are recognized as very promising (Diez-Pascual, 2018). Among metal-containing zeolites, those containing silver are considered to be the most active against a wide range of microorganisms, but the high cost and scarcity of silver prevents the widespread introduction of such bactericidal materials into practice. Therefore, the production of Zn- or Cu- containing zeolite fillers was of interest.

The work involves investigation of the properties of paper obtained by introducing various fillers derived from environmentally friendly raw materials (zeolite), including pre-prepared ones, as well as mixtures of zeolite and salts in various ratios. Zeolites are micro- and nanoporous crystalline aluminosilicates used as substitute for synthetic molecular sieves, adsorbents, ion exchangers and catalysts in industry, agriculture, and environment protection. Heulandite-clinoptilolite of the Dzegvi-Tedzami deposit, the Rkoni plot, was used as the starting material; such a choice from a wide range of zeolites of Georgia was made due to its properties (high content of the zeolite phase and exchangeable alkali and alkaline earth metal ions), as well as the fact that the 2013 EU Regulation No 651/2013 (9 July 2013) confirms the safety of clinoptilolite for use in feed additives for animal species, consumed by humans, so we can state that the fillers and the resulting paper samples are safe to use.

Preparation of zeolite samples includes steps: grinding using standard crusher and planetary mill; fractionation to the required fineness with a set of sieves; drying under static conditions at 95-100 °C; pretreatment includes chemical modification or thermal treatment.

This work is devoted to establishing the optimal method of zeolite pretreatment to obtain paper with a maximum bacteriostatic action against some microorganisms. Evaluation of the bacteriostatic activity of metal-zeolite-containing paper is carried out by the disk diffusion (Kirby-Bauer) method using the cultures of Gram-negative bacteria, Gram-positive bacteria, fungal pathogenic yeast and a fungus. As a result of the experiment, a wide range of paper samples with zeolite fillers was obtained, from which prototypes were selected. The highest bacteriostatic activity in relation to all studied bacteria and fungi is exhibited by Zn-containing paper, containing untreated zeolite; Zn-containing paper, containing zeolite pre-heat-treated at 400 °C; and Zn- and Cu-containing paper, containing zeolite pre-treated with hydrochloric acid, at concentrations of 0.5N and 2N, respectively.

Diez-Pascual A.M. (2018) - Antibacterial Activity of Nanomaterials. Nanomaterials, 8(6), 359, https://doi.org/10.3390/nano8060359.

The non-constant decay constant of ^{187}Re

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Keywords: geochronology, Re-Os dating.

The Re–Os dating method makes use of the decay of ^{187}Re to ^{187}Os. Re and Os are ultratrace elements, among the ten rarest elements in the Solar System, with concentrations below 500 ng/g. Both are siderophile, *i.e*. they are enriched in planetary cores. In iron meteorites their median concentrations are enriched ~100 times relative to the meteoritic median. Os, a highly siderophile platinum-group element (PGE), is extremely depleted in the silicate Earth relative to the iron-nickel core; it is even more depleted in the crust relative to the mantle. Re is a transition element and is moderately enriched in the crust relative to the mantle. Dating requires a disproportionation between Re and Os; however, the rarity of both parent and daughter isotope severely limits application of the Re–Os method for precise geochronology of magmatic and metamorphic rocks. Enrichment of ^{187}Re relative to ^{187}Os especially occurs in sulfide ores; it was used since 1967 to date Archean PGE ore deposits. The use of molybdenite and other sulfides as Re-Os chronometers is the main application of Re-Os (Stein et al., 1998). Ore deposits are notoriously difficult to date by other geochronometers, as usually ores are not cogenetic with magmatic minerals (*e.g*. those commonly dated by U–Pb), since they were formed by late-stage metasomatic, sulfide-rich fluids. The organophile behavior of Re also allowed direct dating of otherwise undatable hydrocarbon deposits in the literature.

The ^{187}Re half-life is exceptional among nuclides used in geochronology, as it is not constant. Normally processes occurring in the atomic nucleus are not influenced by chemical bonds, as the energies involved differ by several orders of magnitude. However, the beta decay of ^{187}Re has an extremely low transition energy (*ca*. 2.5 keV), which makes it possible for the ejected electron to be reflected by the surrounding heavy atoms, a quantum effect called Beta Environmental Fine Structure (Koonin, 1991). Additional effects (capture of the ejected low-energy electron into a bound state, shift of the end-point energy due to the ionization state, etc) have yet to be quantified. The very precise experimental determination of the ^{187}Re half-life in pure Re metal, 41.2±0.1 Ga (Galeazzi et al., 2000) is lower than that in silver perrhenate, $AgReO_4$, 43.2±0.3 Ga (Arnaboldi et al., 2006), where the Re^{7+} ion is surrounded by light O ions. Literature half-lives of 41.5–41.6 Ga were determined on iron meteorites and on molybdenite by comparing the Re-Os age with the independently known age of the samples. The < 1% increase of half-life in a matrix of Fe and Mo, whose first-neighbor atoms of Re are less heavy than first-neighbor atoms in metallic Re and heavier than first-neighbor oxygen atoms in $AgReO_4$, follows the trend predicted by Koonin (1991). The effect of the ionization state on the end-point energy could be as high as 1% but is not quantified.

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Tracking deep energy production and migration across orogenic cycles through fluid inclusion isotope analysis

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Keywords: fluid inclusions, carbon fluxes, natural hydrogen.

Reconstructing geological processes in deep time and space is a key aspect of geology, and a fundamental tool to reconstruct how our planet has maintained habitable conditions though billions of years. Microscopic to nanoscopic objects in rocks and minerals can disclose information enabling access to undisclosed natural secrets. Among these objects, fluid inclusions have long been used to infer on the nature and origine of deep fluids inside the Earth. In this contribution, we push the use of fluid inclusions towards previously unexplored applications aimed at reconstructing the genesis, migration and transformation of deep abiotic energy sources inside the crust. We present results of fluid inclusion extraction and isotope analyses aimed at tracking the evolution of H_2 and CH_4 in the Appalachian belt. Though a mapping-driven approach, our results allowed reconstructing multiple events of CH_4 formations, either abiotic or biotic, and their mixing during fluid-rock interaction events spanning more than 70 Ma and across two or even three orogenic events.

S5.

A journey through planetary geology: Insights from remote sensing, petrographic and mineral studies

Conveners and Chairpersons

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Non-destructive techniques for the analyses of sensitive extraterrestrial materials: the case of Tarda meteorite

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Keywords: meteorite, non-destructive analyses, carbonaceous chondrite.

Tarda meteorite represents a valuable resource for understanding the formation, composition, and evolution of D-type asteroids, as well as the processes that shape carbonaceous chondrites. Its study has significant implications for sample return missions, as it provides a framework for interpreting the mineralogical, chemical, and organic signatures of asteroid samples. This meteorite fell near the locality of Tarda in Morocco on August 25th, 2020 (Chennaoui, 2021) and was readily collected after the fall; thus its original composition is quite preserved.

Tarda is a very peculiar carbonaceous chondrite (Marrocchi et al., 2021), not only for studying the early solar system's conditions and processes, but also since it is mainly black or very dark grey, porous, fragile and easily crumbled with a low density (Chennaoui, 2021), implying that caution should be paid in the preparation of this kind of friable and sensitive material In this view, non-destructive techniques ensure that the sample remains intact for future research and verification of findings (Agrosì et al., 2025).

With this aim we show some preliminary results acquired combining multimethod non-destructive investigations of a crusted sample of Tarda. Chemical and mineralogical analyses by SEM-EDS, chemical mapping and SEM-BSE images were compared with 3D reconstruction by X-ray micro-computed tomography (μ-CT), with the aim to visualize the mineral distribution, texture, porosity and microstructures. The FTIR spectroscopy was used to investigate hydrated phases like phyllosilicates and organic matter occurring in our sample. Our investigations show the occurrence of forsteritic olivine, Ca and Mg sulphates, Fe sulfides and spinels. Moreover, a comparison between BSE images and μ-CT cross-sections reveal the presence of a fusion crust characterized by high density of vesicles and Fe-oxides. Little grains of kamacite, magnetite, Ca-Mg sulfates, Ca-phosphates and Ca,Fe, Mg carbonates were also found.

FTIR spectroscopy measurements were taken using the CAPSULA laboratory setup at IAPS-INAF (De Angelis et al., 2024). The setup allows to acquire spectra of samples in the IR spectral range between 1 and 12 mm at variable ambient pressure (down to 10^{-8} mbar) and in a wide range of cryogenic temperatures down to ~37K. The sample was analyzed with a spatial spot of about 3-4 mm and spectral resolution of less than 0.1 nm. The FTIR could give information on the occurrence of hydrated phases: in fact, OH and H_2O absorptions were found corresponding to 1.4, 1.9, 2.75-3 μm bands. The absorptions at 10–10.3 μm and 11.176 μm are strongly consistent with silicates/phyllosilicates. Furthermore, organics- related absorptions, probably aliphatics, were found in the range 3.4-3.5 μm.

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Mineralogical and geochemical characterisation of a new lunar meteorite

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Keywords: lunar feldspatic breccia, new meteorite, classification.

The investigated meteorite sample was found in Erfoud, Morocco, North Western Africa (NWA) region in 2002, donated to the University of Padova in 2022 and nowadays exhibits at the Museum of Humankind of the University of Padova. Detailed petrographic analysis reveals a breccia characterised by a fine-grain matrix incorporating lithic clasts of anorthosite and impact melt lithologies. In addition to mineral fragments predominantly composed of anorthitic plagioclase, low-Ca pyroxene, minor olivine, and accessory ilmenite were also detected. The fine-grained matrix exhibits extensive comminution and shock features, consistent with regolith processing on the lunar surface. Scanning Electron Microscopy with Field-Emission Electron Microprobe Analyzer (FE-EMPA) delineates the mineral chemistry, confirming anorthitic plagioclase ($An_{93–94}$), Mg-rich olivine ($Fo_{66±10}$) and low-Ca pyroxene (Fs 31±6 wt% and Wo 27±5 wt%) as the dominant phases. Several impact melt clasts were observed, such as glass spherules, melt veins and mosaicism on pyroxenes and plagioclase. These display heterogeneous Ca, Fe, and Ti abundance, but a general enrichment with respect to less shocked materials, reflecting complex shock and thermal histories (Joy et al., 2010). Trace element data provide further constraints on the geochemical affinity of the meteorite. Trace element data for pyroxenes and plagioclase are consistent with a Ferroan Anorthosite (FAN) affinity. All plagioclase clasts display a marked (but variable) positive Eu anomaly (Eu_n/Eu_n = 28–209), suggesting that the different plagioclase clasts crystallized at different stages of magmatic evolution. This interpretation is also supported by the Eu_n/Sm_n versus Sm diagram. The REE patterns of pyroxenes, characterized by a strong negative Eu anomaly and La_n/Sm_n and Gd_n/Yb_n ratios, suggest that the pyroxenes crystallized during the late stages, after plagioclase crystallization, from a residual melt that was highly enriched in iron and in elements incompatible with plagioclase. All these observations could suggest that the clasts of the anorthositic breccia crystallized from parental melts with similar geochemical affinity, but that crystallization occurred at different stages of magmatic evolution. Additionally, bulk geochemical ratios, including FeO/MnO, are consistent with a provenance from the Feldspathic Highlands Terrane and exclude significant mare basaltic contributions (Korotev, 2005). The mineralogical and geochemical evidence supports the classification of this sample as a lunar feldspatic regolith breccia. The provisional name of the submitted meteorite is NWA 15680.

This study demonstrates the efficacy of combined SEM-FE-EMPA and LA-ICP-MS methodologies for resolving the complex lithological and geochemical characteristics of lunar regolith breccias, thereby advancing our understanding of lunar crustal evolution and impact processes beyond the Apollo and Luna collection sites.

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Exploring ice accumulation in Mercury's polar regions: a chronological approach

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Keywords: Mercury, ice, PSR.

Mercury's polar regions are home to Permanently Shadowed Regions (PSRs), where stable thermal conditions allow water ice to persist over geological timescales. These regions have been confirmed as sites of water ice accumulation through Earth-based radar observations and data from the NASA MESSENGER mission, which identified radar-bright deposits with reflectance properties indicative of water ice and other volatiles (Harmon et al., 2011). Understanding the origin and evolution of these ice deposits is crucial for interpreting Mercury's history and comparing it with other planetary bodies. Theories propose multiple sources for the ice, including cometary and asteroid impacts, as well as solar wind implantation. To constrain the age and evolution of these deposits, we employ the crater counting technique on fourteen northern polar craters, analyzing both ejecta and floor materials. By determining the absolute model ages of these craters, we aim to explore correlations between the crater age and ice accumulation, shedding light on the processes driving the formation of ice in PSRs. We selected fourteen polar craters, based on two main criteria: their location in the polar regions and the availability of high-resolution images from the MDIS/NAC and WAC cameras, which allow for detailed mapping of the morphology and surface features. For comparison, six craters located at mid and equatorial latitudes were also included to assess the age differences between the crater floors and ejecta of the polar craters. This comparison was useful to explore the relationship between the presence or absence of ice in the polar craters and how it could affect the floor age. The data for mapping and characterizing the craters were primarily obtained from WAC images from the MESSENGER mission, which offer a spatial resolution ranging from 24 to 110 m/px. To determine the age of the craters and understand their post-impact evolution, a crater counting methodology was applied to both the ejecta deposits and the crater floors.

The polar craters showing a general rejuvenation of their floors in relation to their respective ejecta while the six craters located at low latitudes show floor and the ejecta with the same age. Since at the mid-latitude the rejuvenation of the floor is connected to visible processes and it could be easily explained, at the polar latitude we suggest that the presence of ice could have a role in this resurfacing and rejuvenation mechanism, in particular for the floor with radar bright material. Comparing the percentage of PSR that is radar-bright in specific Earth-based observations within each polar crater with the impact absolute ages, we highlight a correlation between the percentage of PSR that is radar-bright and the age of craters. The older the craters are, the more ice accumulates within the PSRs, except for two craters that are off trend. This trend might indicate that the processes responsible for the accumulation of water ice have been effective and persistent over long geological timescales. The increase of ice with age would relate to a steady state accumulation process, represented by micrometeorite fluxes and solar wind implantation. On the other hand, the two outliers can be explained by episodic delivery of ice, from asteroid and/or cometary impact. We therefore suggest that both the two genetic processes should be considered to evaluate the delivery and the deposition of ice to the polar regions.

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3D electron diffraction of tranquillityite from the Martian shergottite Northwest Africa 856: is its elusive crystal structure one step closer to being finally solved?

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Keywords: tranquillityite, shergottite, 3D electron diffraction.

Tranquillityite, currently defined as $Fe^{2+}_8Zr_2Ti_3Si_3O_{24}$, is a rare silicate first discovered in returned samples from the Apollo 11 mission (Lovering et al., 1971) and subsequently found in meteorites from the Moon and Mars (e.g., Leroux & Cordier, 2006) and as an accessory phase in terrestrial mafic rocks (Rasmussen et al., 2012). Since its discovery more than fifty years ago, its low degree of crystallinity has hindered the determination of its crystal structure. Preliminary crystallographic studies indicated a hexagonal lattice with a = 11.69(05) Å and c = 22.25(10) Å (Lovering et al., 1971). Subsequently, it was discovered that lunar tranquillityite is metamict due to radiation damage by uranium occurring in traces in its structure. Experimental attempts to recrystallize tranquillityite showed a fluorite-related face-centered cubic (FCC) cell with a = 4.85(3) Å (Gatehouse et al., 1977). In-zone electron diffraction by transmission electron microscope (TEM) on preserved crystalline domains in terrestrial tranquillityite showed strong reflections consistent with this FCC cell, but also weaker reflections suggesting a superstructure with both a lower symmetry and a larger unit cell (Rasmussen et al., 2012). Until now, this crystal structure remains elusive.

In this work, we performed wavelength-dispersive X-ray spectroscopy (WDS) by electron probe microanalyzer, electron back-scattered diffraction (EBSD) by scanning electron microscope, focused ion beam, energy-dispersive X-ray spectroscopy and 3D electron diffraction (3DED) by TEM on tranquillityite grains from the Martian shergottite Northwest Africa 856 in order to shed light on its real crystal-chemical features. WDS analyses give the empirical formula (normalized on the basis of 24 oxygen atoms per formula unit): $Fe_{7.70}Mg_{0.54}Ca_{0.17}Mn_{0.11}Zr_{0.97}Nb_{0.03}Ti_{3.19}Al_{0.19}Si_{3.40}O_{24}$. 3D reconstruction of the reciprocal space of tranquillityite can be indexed on a body-centered orthorhombic cell with a = 6.560(10) Å, b = 7.038(11) Å, c = 18.780(29) Å. This cell is consistent with the supercell observed by Rasmussen et al. (2012). Preliminary attempts to solve and refine its crystal structure in the space group *Imma* also show that the cations are packed in distorted face-centered cubes with an average edge of about 4.77 Å in length, similar to the cell parameter of the FCC cell found by previous studies. Despite the great improvement in the structural characterization of tranquillityite, some open issues remain: 1) a good, yet non-perfect match between EBSD and 3DED data; 2) a rather high residual after the structure refinement; 3) the occurrence of very weak reflections suggesting an even larger cell (also observed in the diffraction pattern by Rasmussen et al., 2012). Further analyses will be performed in order to solve this half-century crystallographic enigma.

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Heterogeneous iron-alkali metasomatism in the shocked CO_3 carbonaceous chondrite Frontier Mountain 90006 recorded by the calcium-aluminium-rich inclusions

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Keywords: carbonaceous chondrite, metasomatism, shock metamorphism.

Ornans-type carbonaceous (CO) chondrites are a group of primitive meteorites with petrologic type 3. They may show little thermal metamorphism combined with fluid-related metasomatism, following a metamorphic sequence from which subtypes 3.0 to 3.8 can be defined (Huss et al., 2006). Frontier Mountain (FRO) 90006 is a CO_3 chondrite with shock stage S4 (Stöffler et al., 1991). It exhibits different shock-related textures, including extensive networks of opaques-rich melt veins, metal-troilite nodules (as in Scott et al., 1992) and microfaults (as those observed in ordinary chondrites by Walton et al., 2025). To assess the potential influence of impact events on metamorphic and metasomatic processes, we conducted petrographic and mineralogical investigations on 64 areas containing calcium-aluminium-rich inclusions (CAIs). We integrated micro-Raman spectroscopy, scanning electron microscopy with energy-dispersive X-ray spectroscopy, focused ion beam and transmission electron microscopy. We observed variable degrees of metamorphism on the studied CAIs: some contain relict hibonite or untransformed melilite (indicative of low metamorphic grade), while the most intensely metamorphosed CAIs contain a high abundance of Na-feldspathoids (mainly nepheline and sodalite) and no melilite. Spinel-group minerals range from Mg-rich spinel *sensu stricto* to Zn-bearing, Fe-rich hercynite and high-Ca pyroxenes range from diopside to Al-Ti-rich fassaite. Ti-oxides occur as perovskite, ilmenite and ulvöspinel. Sulfides usually occur in the most modified CAIs. The presence of such a variety of CAIs displaying distinct metamorphic characteristics complicates a clear assessment of the petrologic subtype for FRO 90006, although the occurrence of melilite and perovskite suggests a subtype < 3.5 (Huss et al., 2006). Consequently, future investigations will focus on other components (e.g., the matrix and the amoeboid olivine aggregates) to improve our understanding of the meteorite's thermal history. The observed heterogeneity in metamorphic grades across the studied sample, as recorded by the CAIs, may be attributed to the impact event. It is possible that the impact resulted in the mixing of lithologies that had previously experienced different degrees of thermal metamorphism, or it may be itself the cause of the mobilization of metasomatic fluids.

These findings may have significant implications for our understanding of the dynamic planetary processes that occurred in the early solar system, highlighting the potential role of impact events in producing local redistribution and modification of asteroidal material.

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Quaternary drainage and deposits in the Ahnet basin (Algerian Sahara) - A terrestrial analog for the Hesperian-Amazonian climatic transition in Arabia Terra (Mars)?

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Keywords: Sahara, Mars, climate change.

During the Holocene, the Sahara Desert experienced an alternation between humid and arid phases. The onset of current hyperarid conditions dates to around 6,000 yr. BP, but before that the Sahara was characterized by widespread vegetation and fresh-water due to abundant rainfalls (deMenocal et al., 2000). Evidence of this pluvial phase can still be found in areas nowadays considered to be hyperarid. Among them is the Ahnet Basin, whose Quaternary deposits constitute the focus of our work which aims at:

Improving the understanding of how the wet-to-arid transition influenced the formation of the deposits within the basin;

Assessing the potential of the deposits as analogs for Arabia Terra (Mars)'s deposits experienced similar climatic transitions, particularly at the end of the Hesperian.

The Ahnet Basin (01°00'–04°00' E; 24°00'–27°00' N) is situated in the Algerian Sahara and spans ~65,000 km². Its basement developed during the Pan-African Orogeny (600–500 Ma). The basement is unconformably covered by up to 7 km of Paleozoic sediments primarily consisting in sandstones and shales with sporadic limestone intercalation (Black et al., 1994; Wendt et al., 2006; Perron, 2019). The Mesozoic sequence is absent from the Basin while the Quaternary units, the focus of this study, reflect different depositional processes. Four our study, we selected four areas inside the Ahnet Basin and produced a hybrid geomorphological map for each one of them. In order to create them we used the Sentinel-2A true-color imagery (10 m/pixel) and the Copernicus 30 m DEM combined. The hydrography was digitized using both manual mapping and an automated process through the use of GRASS GIS. Finally, the stratigraphic relationships between the different deposits were studied combining Google Earth hi-res imagery and 3D models. The mapping process allowed us to identify 10 recurring litho-morphological units across all areas, among which we have the units related to the existence of extensive alluvial deposits inside the whole basin. These deposits are associated with a well-developed valley network. This, however, contrasts with the current climatic data which show an annual precipitation rate below 15 mm/yr. In agreement with the current climate is, however, the consistent presence of evaporitic and eolian deposits across all areas. However, analyzing their stratigraphic relationships with the alluvial deposits revealed repeated episodes of channel reactivation and desiccation which from a climatic point of view could only be explained in two different ways:

- A prolonged and gradual climatic transition from humid to arid;
- Isolated and catastrophic precipitations under the current climatic conditions.

Although it is yet to be understood which climatic option among these two is the most correct, this morphological assemblage resembles the one in Arabia Terra suggesting that the Ahnet Basin could represent an analog to better understand the climatic wet-to-arid transition on Mars.

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Comparison of extended hollow fields in Warhol, Hopper, Sander and Eminescu craters

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Keywords: hollows, reflectance, mapping.

Hollows are peculiar surface features that were highlighted by the MESSENGER mission. They are small cavities showing flat-floored and rimless depressions often clustered in fields. They show color variation indicating a higher reflectance and a bluer slope within the 400-1000 nm wavelengths (e.g. Blewett et al. 2013). In literature, it showed for the hollow field in the Dominici crater a potential absorption around 600-700 nm with a subsequent inflection around 1000 nm, which could indicate another absorption. The putative absorption has been attributed to some sulfides (e.g. CaS) or with some chloride (e.g. NaCl) (e.g., Emran & Stack, 2025). Nevertheless, absorption at the same wavelengths could be attributed to mafic silicates, cons,idering transitional elements, different from iron (e.g. Lucchetti et al., 2018). Here we investigated four different hollow fields widespread on the floor of Eminescu, Hopper, Sander and Warhol Craters, considering ad-hoc MDIS 8 color mosaics at different spatial resolutions taking care of the original image resolution. Moreover, the Global BDR, LOI and enhanced color mosaic, as well as high resolution NAC and WAC images were used for morphological mapping. First, we analyzed the color mosaics of Warhol and Hopper craters, at high (385 m/px) and low (1600 m/px) resolution, relatively. We showed that the hollows are principally present on the crater floor, and partially on the exposed bedrock of the central pick, with a higher concentration of hollows around the central pick or on contact with the crater wall. Crater floors are mainly characterized by smooth material representing plains formed due to the refilling after the impact. The Enhanced color mosaics show a widespread distribution of bright and cyan deposits feeding the crater floors and stretching the RGB on regions enriched on hollow fields, we highlighted a color variation emphasizing the fields with respect to the surrounding materials. Moreover, the spectral variation within different regions of interest (R.O.I.) on the hollow fields shows consistent spectra one to each other. In addition, zooming on specific R.O.I.s, the stretched enhanced mosaics match with the pixels showing hollow's morphological evidence, highlighting a reduction of the absorptions where the morphological evidence indicating the hollow disappears.

The spectral variability we investigated seems to highlight as the isolated hollows and hollow fields are characterized by the 600-700 nm absorption and an inflation towards 1000 nm. These hollows spectral properties suggest that they are compositionally different from the surrounding. Which suggests that the spectral properties of the hollows could be to assign to the material inside them, maybe revealing the evidence of the rock forming minerals instead of secondary alteration phases.

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Identification and characterization of a lunar cave by using synthetic aperture radar imaging

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Keywords: lunar caves, synthetic aperture radar.

Lunar pits have been identified as potential clues of the presence of subsurface caves on the Moon. We analyzed synthetic aperture radar (SAR) images captured by the Mini-RF instrument aboard the Lunar Reconnaissance Orbiter in 2010 to investigate a pit on the Mare Tranquillitatis. This is an interesting elliptical skylight with steep walls and a sloping floor. Using novel and ad-hoc advanced radar signal processing techniques (Carrer et al., 2022), we detected reflections consistent with a subsurface cave conduit extending from the pit and reaching tens of meters beneath the surface, thus providing evidence of the presence of an accessible cave (Carrer et al., 2024). This highlights the effectiveness of synthetic aperture radar in exploring lunar subsurface features and represents a first step toward a more systematic analysis of the lunar subsurface. A comprehensive survey of all identified lunar pits using this approach could reveal the most promising access points for subsurface exploration and habitation.

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Minero-chemical investigation of two carbonaceous chondrites: preliminary results on NWA 7317 and NWA 4966

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Keywords: carbonaceous chondrite, mineral chemistry, cosmochemistry.

Among all the meteoritic material, carbonaceous chondrites represent fundamental natural sampling of undifferentiated bodies, and provide essential information about the evolution of the early solar nebula and the subsequent planetesimal formation.

Their early formation ensures the preservation of the initial compositional features typical of the parent bodies they derived from Gattacceca et al. (2020), and that characterised their belonging to a specific group. The occurrence of mineralogical and chemical similarity among the different groups yields to the distinction of clans such as those of CV-CK and CR-CH-CB.

This study, developed in the framework of the Space It Up! project funded by the Italian Space Agency (ASI), and the Ministry of University and Research (MUR), focuses on the mineralogical petrological and chemical analysis of two already classified chondritic meteorites, NWA 7317 (CR6) and NWA 4966 (CK4) to assess their attribution. NWA 7317 has been the subject of few studies in literature (Ruzicka et al., 2015), which proposed its pairing with other meteorites of the CR group (NWA 2994, NWA 3250, NWA 6901 e NWA 6921; Irving et al., 2014; Abe & Mikouchi, 2019), while NWA 4966 has only fragmentary data available.

The mineral chemistry of the main occurring phases (olivine, pyroxene, plagioclase and minor oxides and suphides) and the observed textures are in agreement with the parameters used for classification.

The NWA 7317, in particular, also showed features of equilibration at higher temperatures than those reported for the CR6 type (such as mineral size and femic mineral inclusions within late crystallisation silicates).

In order to better constrain their characteristics and further investigate the processes responsible for their formation we combine mineralogical and geochemical (major and trace elements and Cr isotopes) data to be further compared with the literature. With respect to previous studies, which relied on a limited number of analytical observations, this research allowed to improve the precision and the interpretation of the characteristics of these samples providing a significant contribution to the knowledge of the CK and CR classes.

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Visible to near-infrared reflectance spectra of low-temperature mixtures of water ice and Martian simulant, varying ice texture, dust content and temperatures

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Keywords: Mars, cryosphere, spectroscopy.

The presence of water ice in the polar caps on Mars has been confirmed by several space missions, such as Mars Express (MEX) or Mars Reconnaissance Orbiter (MRO). These are the North Polar Layered Deposits constituted of water ice and inclusions, such as atmospheric dust, not exceeding 5 vol%. Studies of ice-related processes and icy materials in support to space missions are carried out on environmental analogs, such as Antarctica, and using synthetic ice mixtures in the laboratory. In particular, laboratory reflectance analysis should give information about the nature and the quantity of the inclusions into the polar layers. In this work, we have produced synthetic icy-dusty samples in conditions similar to those in the upper part of the North Polar Cap on Mars and we have studied their reflectance spectra from 400 to 4000 nm. The finest grains of the Martian dust simulant MGS-1 (Cannon et al., 2019), that appeared to be similar to atmospheric dust entrapped in the polar layers in terms of spectra and grainsize, was mixed with deionized water to create different icy samples: 250 µm-thick icy slabs as described in Costa et al. (2025), granular ice with diameters of 70±30 µm as described in Pommerol et al. (2019) and compacted ice through pressing of granular ice. We also varied the amount of dust simulant in the icy mixtures from 0 to 5 vol% dust. The spectro-gonio radiometer SHINE and its cryogenic environmental chamber CarboN-IR were used to acquire reflectance spectra in Martian polar-like conditions: temperature ranging from 153 to 253 K and N_2 atmosphere at a pressure of around 10 mbar. Results shows that i) with increasing amount of dust, absorption features in the VIS range appear and progressively become deeper whereas features in the NIR range becomes shallower, ii) temperature increase causes the shift to higher reflectance values and disappearance of the 1650 nm band, iii) granular and, secondly, compacted ices have inter-band intensities that progressively decrease from visible to Near-IR generating a "blue" slope compared to icy slabs. Moreover, granular and compacted ices show marked shoulder asymmetry and larger band depth with respect to icy slabs. The positions of the spectral features in the measured wavelength range do not change with the different kinds of icy samples (slab, granular and compacted ice). The final step will be the comparison of these laboratory spectra with those collected by the NASA MRO-CRISM (Murchie et al., 2007). On first impression, the top of the North Polar Cap is more similar to granular and compacted ice, because it shows "blue" slope of inter-bands, while the layered stratigraphy shows a high level of compaction, thus spectral features similar to icy slabs. However, more analysis is needed to consolidate the comparison and eventual similarity between synthetic sample and Martian spectra.

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Evidence for a new carbonaceous chondrite (CX) group

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Keywords: carbonaceous chondrite, classification, chromium isotopes.

Thanks to the results in a companion study of geochemical composition and $\Delta^{17}O$-$\varepsilon^{54}Cr$ isotopic systematics, the brachinite NWA 13489 has been recently suggested to be an ungrouped primitive achondrite with carbonaceous affinity. Its petro-mineralogic-geochemical similarities with other ungrouped achondrites, namely NWA 10503 and NWA 10859, prompted us to investigate other meteorites which could be related to, like the C3-ungrouped NWA 11961 and another brachinite, NWA 12573, which displays anomalous petrographic and mineralogic features compared to other brachinites, making all of them possible candidates of a new carbonaceous chondrite group informally named "CX" (Irving et al., 2018).

Here we present some preliminary data on the mineral chemistry of these meteorites, that strongly suggests a common origin for these five samples, reinforcing the "CX" group existence hypothesize. While NWA 11961 shows a chondritic texture (chondrules mean size 1110±680 μm, N=77), NWA 10503, NWA 10859 and NWA 12573 show petrographic (i.e., recrystallized granoblastic textures) and mineralogic features nearly identical to those of NWA 13489. In particular, NWA 12573 shows a slightly higher Fa content (mean $Fa_{35.0\pm0.5}$, FeO/MnO = 87.2±3.9) compared to 10503/10859/13489 (mean $Fa_{31.7\pm0.3}$ / $Fa_{30.8\pm0.2}$ / $Fa_{31.1\pm0.6}$ and FeO/MnO = 82.9±4.0 / 83.5±3.4 / 82.9±3.8, respectively). In 10503/10859/13489 the only pyroxene is clinopyroxene, while in NWA 12573 orthopyroxene is the main pyroxene (with different Cr_2O_3-Al_2O_3-MnO compositions from brachinites) with subordinate clinopyroxene. Plagioclases describe a trend line with 10503/10859/12573/13489 in An(mol)-K(a.p.f.u) space, well defined and parallel to the brachinite one. NWA 10503 and 12573 bulk major elements composition (calculated through modal recombination) is similar to that of NWA 13489 and compatible with a carbonaceous-like source (e.g., higher Fe/Mn and Al/Mn compared to ordinary chondrites and brachinites. The trace element composition of NWA 10503 presents a slightly descending REE pattern (compared to the nearly flat one of NWA 13489) with a LREE enrichment and a small negative Eu anomaly. The high ZrCI contents (i.e., 2.2-2.7xCI for NWA 10503 and NWA 13489) exclude any relationship with known carbonaceous meteorite groups (Braukmuller et al., 2018). Also chromium isotopic composition for NWA 10503 agrees with that of NWA 13489, well far away from the brachinites reference composition.

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Microchemical and mineralogical characterization of lunar meteorites aimed at the production and testing of lunar regolith simulants

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Keywords: lunar simulant, lunar meteorites, lunar regolith.

Introduction: Lunar soil simulants have been produced since 1971, as the upcoming space missions needed astronauts to be trained in conducting scientific field works on the Moon's surface. (Slabic et al., 2024) However, the first lunar soil simulants were not satisfactory in terms of chemical composition and mineralogy, as they were focused on having the proper engineering properties. Due to the scarcity and limited accessibility of real lunar soils and rocks samples, and as the interest in lunar colonization with In-Situ Resource Utilization (ISRU) is growing, the production of lunar soil simulants has increased over the years (Taylor et al., 2016). The objective of our work is to develop a new lunar regolith simulant providing a reliable analog in terms of both mineralogy and bulk chemical composition that could be used for experiments on element extraction and for sintering experiments aimed at the production of building materials. Anorthositic rocks are major constituents of the highland regions of the Moon (Jaumann et al., 2012), so we aim at reproducing the composition of a regolith whose major component is anorthositic. As lunar meteorites give access to unsampled areas of the Moon's surface (Korotev, 2005), we analyzed microchemically and mineralogically feldspathic lunar breccias and use their chemical composition and modal mineralogy as a reference.

Samples and Methods: We performed microchemical and mineralogical characterization of some lunar feldspathic breccias, specifically of samples of the meteorites NWA 7948, NWA 11273, Bechar 007 and Gadamis 004, four feldspathic lunar breccias with low weathering grade. The samples were analyzed through FE-SEM at the University of Camerino and the University of Perugia and FE-EMPA analyses are planned at the University of Firenze. Operation conditions were working distance of 8.5 mm and accelerating voltage of 15 and 20 kV. We started with synthesizing anorthite plagioclase and fluorapatite. We plan to synthetize glass whose composition resembles that of impact glass, vesicular glass of the agglutinates, and volcanic spherules found on lunar rocks and lunar meteorites. The next step will be to find natural terrestrial pyroxenes and olivines of suitable chemical composition and to add them in adequate amounts.

Results: Petrographic and microchemical investigations on the cited meteorites revealed the dominance of anorthitic plagioclase with average composition $An_{96.1}Ab_{3.7}Or_{0.2}$ and therefore we focused on the synthesis of anorthite microcrystalline powders with this chemical composition using a muffle furnace in air. Synthesis of fluorapatite is currently ongoing, as is the analysis of terrestrial pyroxenes and olivines.

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First Instances of Venusian Lava Tubes

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Keywords: Venus, lava tubes.

The existence of lava tubes on planetary bodies has long been a subject of interest in planetary geology, with confirmed cases on the Moon, Mars, and Earth (Sauro et al., 2020). These subsurface cavities offer insights into volcanic processes and are prime targets for the Subsurface Radar Sounder (SRS) on the EnVision Venus mission, designed to penetrate several hundred meters below the surface. However, observational limitations have kept the presence of lava tubes on Venus speculative until now.

We present the first compelling evidence for lava tubes on Venus, based on an extensive analysis of pit alignments on Venusian volcanoes over 100 km in diameter (Hahn & Byrne, 2023), utilizing Magellan's radar imagery and topography.

Our survey revealed four distinct sinuous pit chain instances not associated with tectonic extensional structures. These alignments exhibit characteristics consistent with collapse features observed above lava tubes on other planetary bodies: (1) Morphometry: the identified pit alignments display a curvilinear arrangement in plan-view, typical of collapsed lava tube sections, exhibiting higher sinuosity than tectonic pit chain samples. (2) Dimensions: pits' width and depth cannot exceed the underlying lava tube's, while tectonic pit diameters correlate with depth. (3) Geological context: all instances occur on shield volcano flanks with extensive lava flows and their direction aligns with observed terrain slopes, consistent with lava flowing on an inclined surface.

Additionally, the inferred cavity geometry matches the crusting-over process typically associated with non-inflating lava tube development (Hon et al., 1994; Peterson et al., 1994), involving upper lava flow solidification while underlying molten lava drains, leaving a hollow conduit. However, the estimated Venusian lava tube volumes based on visible pit alignment extents and assumed continuity between collapse features are comparable to lunar cases (Fig.1), implying cavities larger than those on Earth (Sauro et al., 2020).

This study presents the first observational evidence for lava tubes on Venus, significantly expanding our understanding of the planet's volcanic processes. Discovering these structures enhances our knowledge of planetary speleogenesis and has implications for future exploration strategies. The observed Venusian lava tubes' characteristics, particularly their large scale, suggest Venus may host some of the most extensive subsurface cavities in the solar system. However, current observational data limitations emphasize the need for future high-resolution imaging missions to fully map and characterize Venus' lava tube systems.

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New observations on EET87746 Antarctic meteorite by non-destructive analyses

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Keywords: meteorite, mineralogy, microcomputed tomography.

In recent years, non-destructive techniques have proven essential for the study of important and scientifically valuable extraterrestrial samples. These methodologies, in fact, guarantee the integrity of the samples making them available to the scientific community for further analyses and validation.

With this objective, a fragment of EET 87746, an Antarctic meteorite found in 1987 during the expeditions of the ANSMET (ANtarctic Search for METeorites) program at Elephant Moraine (Antarctica) is in progress. It is an enstatite chondrite EH4 type. On the outer part, EET87746 is very altered and there are several deep fractures. 60% of the surface is characterized by a black fusion crust (Carol Schwartz, 1989).

The aim of this study is to investigate the mineralogical composition of the meteorite, with particular focus on rare phases, mineral distribution and associations, textures and microstructures, to gain further insights into its origin and evolutionary history.

The mineralogical and chemical composition of EET87746 was investigated using Scanning Electron Microscopy (SEM) and μ-Raman spectroscopy. These techniques were associated with the micro-computed tomography (μ-CT), a useful methodology to investigate porosity and to obtain volumetric data without sample destruction (Manzari et al., 2023; Agrosì et al., 2025)

Preliminary results show that EET87746 consists of chondrules formed by pyroxene (enstatite) immersed in a plagioclase mesostases. We have recognized also nickel-iron alloys, sulfides (troilite, daubréelite and oldhamite) and phosphides (schreibersite). Furthermore, this meteorite shows signs of surface alteration due to prolonged exposure to atmospheric agents. Indeed, it is important to highlight the presence of oxidised phases (such as jarosite and limonite) that are the sign of a heavily weathering, according to Bryan Mason (1989) and Carol Schwartz (1989). Despite this, the internal features of EET87746 are well preserved and CAIs are also present. The data extrapolated from the μ-CT (in progress) will be correlated to the chemicalmineralogical composition. This will provide new compositional, porosity and mineralogical information without destroying the sample.

Agrosì G. et al. (2025) - Unique (Al, Cu)-alloys discovered in a micrometeorite from Southern Italy. Commun. Earth Environ, 1-10.

Manzari P. et al. (2023) - New insights on the porosity and grain features of Al Haggounia 001, an impact-melt meteorite. Lithos, 438.439, 107015.

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Studying extraterrestrial bodies by non-destructive methods: the case of GRO 95517 Antarctic meteorite

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Keywords: meteorite, microcomputed tomography, non-destructive methods.

Returning sample missions have gained increasing attention in the last decades since the only way to know the planetary surface's composition and to reconstruct the history of geological processes is to analyse samples using Earth-ground laboratory-based techniques. The employment of a non-or minimally destructive protocol of analyses to carry out a comprehensive characterisation is crucial to preserving very precious extraterrestrial samples. On the other hand, non-destructive analyses on samples of meteorites and micrometeorites were yet successfully applied on Al-Haggounia 001 (Manzari et al., 2023) and the micrometeorite found on Mt. Gariglione, southern Italy (Agrosì et al., 2025).

With this aim, we are studying a fragment of an Antarctic meteorite named GRO 95517, a EH3 chondrite, found in 1995 in Grosvenor Mountains, Antarctica – NZ (Harvey & Snyder, 1996). The sample was kindly loaned by NASA. The purpose of this investigation is to study mineralogical composition with particular attention to the rare phases, mineral distribution and association, texture and microstructures to provide further information on the origin and evolution of this meteorite.

The fragment was studied by Scanning Electron Microscope (SEM), μ-Raman spectroscopy and microcomputed tomography (μ-CT), a crucial method to obtain bulk information, thanks to the ability to provide 3D reconstruction of meteoritic fragments. The correlation between SEM-EDS data, chemical mapping and images by μ-CT allowed us to obtain volumetric reconstruction of the sample in a non-destructive way, without compromising its integrity. μ-Raman spectra identify the exact polymorphs present in the fragment, helping the reconstruction of the geologic history of meteorite.

The integration of SEM-EDS data and μ-Raman with 3D reconstruction by μ-CT shows that the Antarctic meteorite GRO 95517 is characterized by primary phases such as enstatite which represents the main constituent of chondrules. Furthermore, a significant distribution of sulfides (oldhamite, daubréelite, and troilite) and Fe,Ni alloys were found homogeneously dispersed throughout the sample. Secondary mineralogical phases related to terrestrial weathering alteration (limonite and jarosite) fill up pores and fractures.

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Manzari P. et al. (2023) - New insights on the porosity and grain features of Al Haggounia 001, an impact-melt meteorite. Lithos, 438.439, 107015.

VNIR reflectance spectra of $(NH_4)_2HPO_4$ and $(NH_4)HSO_4$ salts: Effect of low-temperature phase transitions

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Keywords: ammonium salts, icy bodies, reflectance spectra.

The interest in detecting ammonia and ammonium-bearing minerals on icy bodies comes from their key role in subsurface brines, crucial for understanding the dynamics and composition of icy moons. Following the Galileo, Cassini-Huygens, Dawn, and New Horizons missions, many questions arose about the detection and significance of ammonium minerals (Dalle Ore et al., 2019; De Sanctis, 2024). Ammonium compounds have been linked to recent geological activities such as cryovolcanism, tectonic exposure, and impact events. This study investigates the reflectance spectra of two synthetic ammonium salts, ammonium hydrogen phosphate [$(NH_4)_2HPO_4$] and ammonium hydrogen sulphate [$(NH_4)HSO_4$], between 1–4.2 μm and at low temperatures (down to 110 K) collected with the SHINE spectro-gonio radiometer at the IPAG institute, Grenoble (https://cold-spectro.sshade.eu). $(NH_4)_2HPO_4$ undergoes three phase transitions at 416, 246 and 174K (α → β → γ → δ) (Hadrich et al., 2000), while $(NH_4)HSO_4$ is characterised by two phase transitions at ambient pressure with decreasing *T* at 270 and 154K (III → II → I) (Swain et al., 2012). Both salts show absorption features related to $(NH_4)^+$ overtones and combinations in the 1–2.5 μm range (~1.09, ~1.3, ~1.58, ~2.02, ~2.2 μm), useful for discriminating between them. As temperature decreases, absorption bands become sharper with more defined minima and shift to longer wavelengths due to stronger hydrogen bonding. Phase transitions appear as changes in band parameter (position, area, depth, width) and wavelength shifts. For $(NH_4)_2HPO_4$, phase transitions at 246 K and 174 K do not produce abrupt changes but modify the slope of the band parameter, with new bands emerging at ~1.88 and ~2.36 μm. For $(NH_4)HSO_4$, the first transition at 270 K was not detected, being associated with $(HSO_4)^-$ ion ordering, while the second transition at 160 K, involving O-H···O and N-H···O hydrogen bonds, caused clear spectral changes. VNIR spectra of $(NH_4)_2HPO_4$ and $(NH_4)HSO_4$ show $(NH_4)^+$ absorption features whose parameters vary with temperature, especially near phase transitions. In $(NH_4)_2HPO_4$, transitions cause reorganisation without abrupt parameter shifts, mainly altering the slope of temperature-dependent trends. In $(NH_4)HSO_4$, the ferroelectric transition at ~160 K is well detected through spectral changes associated with hydrogen bond ordering. This research enriches the spectral database of ammonium salts at cryogenic temperatures, supporting the interpretation of remote sensing data from missions such as New Horizons, Europa Clipper, JUICE, and JWST, particularly for icy celestial bodies.

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Coesite discovered in Australasian microtektites

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Keywords: tektites, shock metamorphism, impact melting.

Microtektites are microscopic glass spherules produced by large impacts on Earth. Whether they originated as impact melt droplets or as condensates from a vaporized target ± projectile precursor is debated (Del Rio et al., 2025). Combining optical, scanning and transmission electron microscopy, we studied microscopic silica-rich inclusions in four Australasian microtektites to search for high pressure phases produced by shock metamorphism in the precursor materials. Three microtektites are from deep-sea sediment cores close to the putative impact location in Southeast Asia, and one is from the Transantarctic Mountains at the extreme reaches of the strewn field. Inclusions in the deep-sea microtektites consist of few partially resorbed microscopic quartz and coesite crystals set in a silica-rich glass matrix; the latter hosts a multitude of individual nanoscopic and partially resorbed coesite grains. The inclusion in the Antarctic microtektite consists of featureless silica-rich glass, is devoid of coesite and shows diffusive boundaries. Coesite grains in the oceanic microtektites are interpreted as impact melted relicts of larger crystals originally formed during shock metamorphism in a quartz-rich target precursor, in agreement with what proposed for macroscopic tektites (Masotta et al., 2020). The survival of coesite constrains the host microtektite quench time to a few seconds, based on experimental work in the literature. The presence of coesite in oceanic microtektites strengthens the argument that Australasian microtektites found closest to the impact location originated as impact melt spherules upon compression/decompression melting during impact cratering (Folco et al., 2010) and not as target ± projectile vapor condensates (Koefoed et al., 2024). The high degree of digestion of the inclusion in the Antarctic microtektite is in line with the view that the most distal Australasian microtektites experienced the highest thermal regimes (Folco et al., 2010).

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From collection to catalog: the state of meteorite cataloging in Italy through the BN-PL national standard

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Keywords: astromaterial, meteorite collection, cataloging.

The study of astromaterials—comprising meteorites, returned samples, and cosmic dust—affords crucial insights into the Solar System's history and evolution. The scientific relevance of these specimens is determined not only by the analytical data gathered but also by the practices used for their documentation and conservation (Franza & Pratesi, 2021; Franza et al., 2024). In this framework, the implementation of standardized cataloging protocols is not merely an administrative requirement but a foundational procedure that underpins data accessibility, collection integrity, and the broader dissemination of knowledge across the planetary science community.

This contribution focuses on the BN-PL (*Beni Naturalistici – Planetologia*) national cataloging standard, developed by the Central Institute for Cataloging and Documentation (ICCD) under the Italian Ministry of Culture (MiC). BN-PL is specifically tailored to the unique curatorial and scientific practices regarding meteorite collections preserved in museums. As a legally recognized, open-access, and interoperable model, it integrates more than 500 metadata fields organized into 21 thematic sections, encompassing mineralogical and petrographic classification, sample's availability (e.g., fragments, thin sections, mounts), provenance and acquisition information, analytical data, conservation status, appropriate conservative procedures and policies, details about exhibitions and loans, other than an updated bibliography regarding the cataloged specimen (Pratesi & Franza, 2021). It is worth noting that every record is completed with high-resolution images and metadata (e.g., audio-video documentation), further supporting research and public engagement efforts.

After describing the model, this work outlines the current status of cataloging Italian meteorite collections employing the national standard BN-PL, developed by the Central Institute for Cataloging and Documentation (ICCD) under the Italian Ministry of Culture (MiC). To date (May 2025), 1095 samples – primarily from Tuscany (n = 985) and Emilia Romagna (n = 110) – have been cataloged out of 68810 natural specimens nationwide. These data highlight the limited adoption of the BN-PL national standard, resulting in numerous meteorite collections remaining undocumented and largely inaccessible to the scientific community. Consequently, critical information that could advance planetary sciences, as well as essential data regarding the conservation status of these rare materials, risks being lost or overlooked. Furthermore, the limited usage of BN-PL reveals systemic challenges that hinder broader implementation, such as the complexity of retrospective cataloging, a lack of specialized personnel, and insufficient institutional resources. Addressing this gap requires targeted training programs and increased institutional collaboration to promote the adoption of BN-PL as a reference standard.

In conclusion, BN-PL offers a valid, scalable solution for the stewardship of Italy's astromaterial heritage. Its expanded adoption holds the potential to transform local documentation practices into a cohesive, nationally integrated system—one capable of meeting both current research needs and the demands of future planetary exploration missions. As the scientific and cultural value of astromaterials continues to grow, we must likewise strengthen our commitment to ensuring their responsible and accessible documentation.

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The geology of north-eastern Tempe Terra, Mars

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Keywords: planetary geology, Mars, geological mapping.

The Martian dichotomy has always attracted the interest of science. Looking at the Martian global topography, the elevated cratered regions of the southern hemisphere contrast with the relatively smooth terrain north of the dichotomy. At the global scale, the transition between the southern highlands and northern lowland plains occurs on a sinuous boundary where topographic elevations drop 2000 to 4000 meters in a few hundred kilometers, with regional slopes of about 1 degree, two orders of magnitude larger than the southern and northern hemispheres alone (Zuber et al., 1992).

Here we report our study of the geology of the northeast of Tempe Terra, between the Syntiskaya crater and Tempe Fossae (42.5-47.5 °N, 300.0-305.0 °E). Through geologic mapping, we traced the elements for the description of the evolution of the area, from morphologic features to the definition of geologic units with their stratigraphic relationships and absolute ages through crater size-frequency distribution (Frigeri et al., 2025).

The regional topography in the study area dips towards the northeast, with a total elevation decrease of about 2000 meters. Plateaus constitute the general morphology of the area with their flat, slightly dipping surfaces set at different elevations. The geologic setting is generally monoclinal, with the topmost unit exposing layering along the steep cliffs, visible from moderate resolution remote-sensing imagery. Crater size frequency distribution analysis indicates geologic unit ages of 3.8 to 3.4 Ga. A set of parallel elongated valleys oriented NNE-SSW shows mounds, pitted terrain, and fan deltas. The action of erosion is evident in the lower plateau unit, where we found evidence for inverted morphologies of old channels and craters. The main tectonic features of the area are wrinkle ridges and linear fractures. Linear fractures are oriented ENE-WSW, similar to the general trend of the Tempe Terra fault system.

Crater floors and ejecta show a wide range of deposits, mostly interpreted as the product of impact on a volatile-rich underground. Among the others, the area contains a series of 0.5 to 2 km wide fresh craters. Furnari et al. (2024) studied one of these craters using spectral analysis, highlighting an anomalously large abundance of seasonal water ice on the ejecta, providing new insights into ice variation in the Martian ground. Additionally, Gou et al. (2024) examined the lowlands Chryse Planitia region to the southeast of our study area, showing evidence that craters with multi-layer ejecta at this latitude indicate the presence of subsurface volatiles.

Our study describes the geologic history of the area from the emplacement of the units to their modification by cratering, fluvial, and ice-related processes. This offers an opportunity to extend our knowledge not only in this study area but also within the context of studies unraveling the history of the climatic evolution of the planet at a broader scale.

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From mineral mapping to Moon bases: ISRU-oriented hyperspectral analysis of lunar terrains

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Keywords: Moon Mineralogy Mapper, ISRU.

From an in situ resource utilization (ISRU) perspective, the selection of landing sites characterized by high mineralogical resource potential is a critical prerequisite for the development of a sustainable lunar infrastructure. This study presents a comparative mineralogical analysis of four geologically diverse regions – Aristarchus, Malapert, Mare Tranquillitatis, and the Leibnitz crater – using hyperspectral data acquired by the Moon Mineralogy Mapper (M³) instrument onboard the Chandrayaan-1 mission (Pieters et al., 2009). These sites were selected based on geological diversity and relevance to future crewed missions, as well as operational constraints such as terrain slope, communication feasibility, and environmental stability. Representative reflectance spectra were extracted from spatially subset M³ data cubes and compared to laboratory spectra from the RELAB database (NASA PDS, 2020) using a suite of established spectral similarity algorithms including Spectral Angle Mapper (SAM), Spectral Information Divergence (SID), and Adaptive Coherence Estimator (ACE), implemented in the ENVI software. Prior to spectral analysis, data underwent standard preprocessing including radiometric, thermal, and photometric correction, followed by spectral denoising. A spatial and spectral subsetting was also performed to isolate the regions of interest and eliminate data anomalies at image edges. The operational hyperspectral workflow followed the established Spectral Hourglass approach, including Minimum Noise Fraction (MNF) transformation, Pixel Purity Index (PPI), N-Dimensional Visualizer clustering, and Linear Spectral Unmixing (LSU). These methods enabled the identification and mapping of key mineralogical units such as plagioclase, low- and high-Ca pyroxenes, ilmenite, and spinel. Notably, the Malapert region showed strong plagioclase signatures consistent with anorthositic highlands, while Mare Tranquillitatis revealed spectral features of high-Ca pyroxenes and ilmenite, indicating basaltic compositions with significant ISRU potential. Through the integration of mineralogical remote sensing data with principles of sustainable design and resource-based site assessment, this work provides a multidisciplinary framework to support the strategic selection of sites for long-duration lunar habitation and development.

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Cisternazza pyroclasts (Mount Etna) as a lunar analog: mineralogical, chemical and spectral insights

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Keywords: planetary geology, analogue sites, lunar regolith simulants.

In the recent years, major space agencies including NASA, ESA, CNSA and JAXA have been planning comprehensive lunar initiatives, including the Artemis program This context underscores the importance collect direct ground-truth data and samples, and test equipment at designated analogue sites. Pyroclastic deposits are key targets: (1) they can be used for the extraction of volatiles like H_2, O_2 and H_2O; (2) their typically high content of amorphous material makes them excellent precursors for geopolymer production (Provis & Van Deventer, 2009). Consequently, these materials represent a promising *in-situ* resource on the Moon (Anand et al., 2012) though their resource potential needs further investigations on Earth analogues in volcanic environments. Analogue sites, such as Lanzarote (Canary Islands) (Mateo et al., 2019) or Kilauea Volcano (USA) have been extensively studied, whereas the compositional similarity of Mount Etna to lunar materials remains unexplored. To investigate the potential analogy of Etna pyroclastic deposits with Moon ones, we collected several samples in the Cisternazza pit crater area, located on Mount Etna's southern flank. We performed a Principal Component Analysis on the X-Ray Fluorescence (XRF) major-element data to highlight only those Etna samples that are like Apollo averages composition and certified simulants. To confirm that chemical analogy translated into mineralogical similarity, we compared the X-Ray Diffraction (XRD) patterns of the PCA-selected samples against lunar reference phases. The sieving of the selected sample has been standardized according to ASTM standards to align the Particle Size Distribution (PSD) with that of Apollo samples. The particle size distribution obtained has been analysed via the Mastersizer 3000. Additional analyses were performed on this material, including hyperspectral acquisition, SEM-EBSD, FTIR, and TGA/DSC. *Results*: Based on the results of the above-mentioned preliminary assessment (XRD-XRF), a single sample — exhibiting the closest affinity to Apollo 14 average composition — was selected for detailed analysis. After the particle-size distribution was created, it was compared with that of Apollo 14, showing close agreement. Further SEM-EBSD analyses of selected ROIs provided elemental data that refined the chemical characterization of the amorphous phase; this information is crucial for optimizing geopolymerization. Because of its pyroclastic origin, the sample contains a high proportion of amorphous material, which gives it a spectral signature very similar to that of Apollo 14 agglutinates. Agglutinates are composite particles sintered together by vesicular, flow-banded glass. Our initial findings hint at intriguing similarities that could significantly impact future lunar-exploration strategies, as the close chemical analogy is essential for carrying out realistic water-extraction tests on regolith (Zanotti et al., 2024) and for advancing the study and testing of geopolymers on Earth.

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A new italian meteorite from Scalea, Cosenza: description and preliminary data

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Keywords: meteorite, fall, ordinary chondrite.

A meteorite recovery in the Italian territory is an extremely rare event, due to unfavorable environmental conditions that do not allow long-term conservation of these stones on the fall site. For this reason and for the presence of numerous urbanized, cultivated, wooded or mountain areas, systematic recovery campaigns on the Italian territory have never been organized in recent times except in cases of recent, instrumentally demonstrable falls. This is the case of the recent meteorite falls of the Cavezzo and Matera meteorites, whose fall was monitored through the all-sky cameras of the Prisma network: in both cases, the determination of the fall area consented a relatively easy discovery of centimeter-sized fragments that allowed scientists to perform a complete characterization (Pratesi et al., 2021; Barghini et al., 2024). Recently a very interesting case occurred near the town of Scalea, Cosenza. Mr. Maurizio Sassone, owner of a beach resort in this town, personally witnessed on September 11th, 2024 at 12.34 a.m., the fall of an object a few meters away from him, exactly in the strip of land between the shoreline and the furnishings of his resort. He made a detailed photographic report without removing the object and collected the object and a small quantity of white sand from the surrounding area, placing them in two separate plastic bags. After contacting one of the authors, he subsequently brought the stone to the Meteocert laboratory of the Sistema Museale di Ateneo of the University of Florence where the first investigations regarding its nature were conducted. A first detailed stereoscopic microscope observation confirmed the suspected meteoritic origin of the stone: some distinguishing features, like an almost complete dark brown fusion crust with several small cracks on the external surface, a rounded and oriented shape and several parallel streaks on one side, which appears ablated and partially remelted, support this hypothesis. The external surface a sals somewhere covered by a very fine grained white powder probably due to the impact with the seashore. A small crust-free area revealed a fine grained texture consisting of green and white small crystals, with no visible metal spots, pointing to a possible classification of the meteorite as ordinary chondrite (Grady et al, 2013). The presence of a very small barred-olivine chondrule on the ablated side confirms this hypothesis. Micro-Raman analyses performed on small grains extracted from the crust-free area confirmed the presence of olivine (an term of the fayalite-ferrosilite series), a bronzitic orthopyroxene and an albitic plagioclase. A micro-raman analysis a salso been performed on both the white powder and the original sand of the seashore, both consisting of calcite, confirming the provenance of the meteorite from this site. According to these data the meteorite can be considered a new Italian find, probable fall, from Scalea, belonging to the ordinary chondrite type.

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Process insights from 4 Vesta: a new HED sample

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Keywords: meteorite, howardite, symplectite.

A newly discovered achondritic meteorite, recovered from the Erfoud region (Northwest Africa, Morocco) in 2005, was investigated to determine its petrogenesis and classification. A 30 µm thin section was examined by transmitted-light optical microscopy, revealing a polymictic breccia comprising discrete lithic clasts (0.2–1 mm) in a fine-grained, sharp-edged matrix. Primary phases – pyroxene and anorthitic plagioclase – occur as both phanerocrysts and matrix grains. The textural and petrographic observation suggested a consistency with Vestan eucritic and cumulate lithologies (Mittlefehldt, 2015). The eucritic components of the sample are characterized by the coexistence of clinopyroxene and plagioclase, displaying both cumulate and basaltic textures. Diogenitic components are represented by fine-grained orthopyroxenes dispersed throughout the matrix. Shock microstructures, including undulatory extinction and plagioclase mosaicism, corresponding to shock stage S3, suggest peak pressures of ~10–24 GPa (Stöffler, 2018) and document the sample's complex shock history.

Scanning electron microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) analyses corroborated petrographic observations and confirmed the origin from 4 Vesta. In particular, the Fe/Mn ratio of ~30 is consistent with established HED meteorite values (Nittler et al., 2004). Pyroxene compositions span across a broad range, from enstatitic orthopyroxenes to more Fe- and Ca-rich pigeonite and augite. Plagioclases are predominantly anorthitic ($An_{82–96}$), consistent with eucritic compositions. Accessory minerals, including tridymite, taenite-kamacite, chromite, and troilite, were also detected. Intriguingly, two clasts deviate from typical HED lithologies. The first exhibits a fayalite–anorthite–silica symplectite texture, interpreted as the breakdown product, at pressures below 1 GPa, of high-pressure pyroxferroite. The second displays pronounced alkali and sulfur enrichment (Al_2O_3 up to ~15 wt%, K_2O ~1.5 wt%, S ~1.7 wt%), with fracture-infilling assemblages of troilite, plagioclase, and pyroxene. These features suggest localized metasomatic alteration by S-rich fluids and/or alkali-rich fluid circulation likely derived by exogenous carbonaceous material, thus expanding the known geochemical diversity of Vestan surface materials.

The mineralogy, the petrographic diversity, the shock signatures, and the geochemical heterogeneity support classification of this meteorite as a howardite. Ongoing studies on this sample will aid in adding the complex interplay of magmatism, impact metamorphism, and fluid–rock interactions on asteroid 4 Vesta.

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Size distribution of scoriaceous and unmelted micrometeorites from the transantarctic mountains micrometeorite collection

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Keywords: unmelted micrometeorites, scoriaceous micrometeorites, size distribution.

Micrometeorites (MMs) dominate the flux of extraterrestrial material that falls to the Earth's surface. They are classified according to the degree of melting into three groups: melted micrometeorites (cosmic spherules, CSs), unmelted micrometeorites (UnMMs) and partially melted scoriaceous micrometeorites (ScMMs) (Genge et al., 2008). A significant number of large UnMMs and ScMMs were recovered from 1-2 Myrs old sediments traps in the Transantarctic Mountains (TAM) (Rochette et al., 2008; Suttle & Folco, 2020). We report an unprecedented, statistically significant study (N = 227) of the size distribution of ScMMs and UnMMs in the 200-2800 μm size range. This study contributes to the definition of the MMs flux to Earth over the Quaternary. Particles were weighed using a microbalance and imaged under a FEG-SEM at CISUP, in order to define their mass and size. Identification of UnMMs and ScMMs was based on textural features observed via back-scattered electron imaging. Subsequently, the MMs were scanned using X-ray computed microtomography (XmCT) at the ZAG institute, for a 3D textural classification into fine- or coarse-grained UnMMs and ScMMs.

The size distribution of the UnMMs and ScMMs is bimodal, with two main peaks at 300 and 500 μm. A similar bimodal distribution was observed in TAM CSs, yet shift towards lower sizes with peaks at 145 and 250 μm (Suttle & Folco, 2020). The discrepancy in the bimodal distribution of UnMMs and ScMMs versus CSs in the TAM collection could reflect to the size-mass reduction produced by atmospheric entry heating leading to evaporative loss on a single population of extraterrestrial dust. As suggested earlier based on totally melted CSs (Cordier & Folco, 2014; Suttle & Folco, 2020), the bimodal distribution in the micrometeorite flux could potentially indicate at least two main sources for the near-Earth interplanetary dust complex, namely dry, coarse-grained and evolved bodies (inner main belt asteroids), or hydrous, fine-grained and primitive bodies (outer main belt asteroids and comets). The classification based on XmCT scans is currently in progress. One-third of the collection has been classified and shows two distinct peaks in the size distribution of the fine- and coarse-grained MMs. The coarse-grained MMs show a peak at 600 μm, while the fine-grained MMs show a peak at 400 μm, as well as a lack of particles with diameters greater than 1100 μm. This evidence from ScMMs plus UnMMs that still preserves primary textural features (in contrast to CSs) documents that grain-size in the precursor material is a factor for the bimodal size distribution observed in the micrometeorite flux. The analysis of XmCT data will also provide information on the volume, density, porosity and weathering of these particles.

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Preliminary analysis of aeolian bedforms present in the Eberswalde preserved delta, Mars

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Keywords: aeolian bedforms, atmospheric circulation, environmental changes.

Eberswalde crater (33° W, 24° S), situated NNE of Holden crater, lies along an ancient fluvial corridor linking Argyre basin to Ares Vallis. Crater formation is constrained to the Early–Late Hesperian by Holden's ejecta blanket (Irwin & Grant, 2011). Its interior hosts well preserved fluvio-lacustrine deposits. These deposits were eroded by aeolian processes which, in recent to present times, reworked part of this material forming aeolian bedforms. The goal of this study was to map these bedforms to realize a stratigraphy of aeolian deposits to infer changes in wind circulation which would reflect atmospheric circulation, and in turn climate changes on the recent Mars. To achieve this, co-registered and orthorectified CTX mosaics and HiRISE images and DEMs were processed using Integrated Software for Imagers and Spectrometers (ISIS) and NASA Ames Stereo Pipeline (ASP), and then integrated in a GIS system. Preliminary results reveal two principal bedform classes: dunes with crest spacings of ~260 m and heights of 1–6 m, and megaripples with 1–2 m heights and 30–40 m wavelengths (Silvestro et al., 2020). Both star and barchan dunes coexist. Wind azimuths reconstructed from crest orientations reflect temporal variability in prevailing winds. Star dunes characterized by radiating arms indicate highly variable, multidirectional flow, whereas barchans (~3–4 m high) point to unidirectional regimes. Older bedforms from an earlier wind regime are often overlain or truncated by younger ones, evidencing at least two distinct aeolian episodes. Larger wavelengths align with older, smaller wavelengths mark later. Variations in inter-crest spacing capture shifts in sediment availability. Ongoing work will include a complete mapping of the Eberswalde basin in order to constrain the stratigraphic reconstruction and the topography influence on winds direction. Moreover, crater size–frequency analysis will be attempted to date the mapped bedforms. This will refine timing estimates for wind regimes and will constrain the changes in wind circulation pattern and their significance for a climatic change.

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The interaction of crystalline and amorphous phases in the determination of VNIR and MIR spectral signatures: insights from the PVRG rock spectra database

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Keywords: spectroscopy, experimental, database.

Magmatism and volcanism are key processes that shaped the surface of rocky planets in the Solar System, and understanding how magmatism occurred on these planets is essential to reconstruct their geological histories. It is very likely that volcanic terrains on planetary surfaces are covered by products that have a porphyric, aphanitic, or hyalocrystalline texture, in which crystalline phases represent only a fraction of the rocks that are mainly composed of amorphous materials such as glasses. Remote investigation of planetary surfaces combines geomorphological analysis with spectral data. Regarding the latter, the interpretation of spectral information from planetary terrains needs to be based on the comparison with reference material.

Up to now, libraries and repositories mostly report information about so-called planetary analogues, consisting of crystalline materials rather than amorphous products. This happens because of the lack of spectral features of amorphous products. However, the presence of amorphous material together with crystalline phases deeply influences the spectral response of the latter (Horgan et al., 2014). For this reason, the Petro-Volcanology Research Group at the University of Perugia started to build up a spectral database of volcanic rocks, both natural and synthetic, to understand how and how much crystalline and amorphous products influence each other in determining the spectral response of a rock/terrain. In this work, we report the spectral characterization of various products within two ranges: Visible and Near Infrared (VNIR) and Mid-Infrared (MIR). The accounted products consist of:

- Synthetic silicate glasses with a wide range of chemical composition (Pisello et al., 2022a, 2022b)
- Synthetic planetary analogues consisting of rocky materials containing both amorphous and crystalline products (Pisello et al., 2024)
- Natural volcanic rocks.

The overall analysis of the spectral response shows that, within the MIR, it is relatively easy to link the wavelength position of well-known spectral features (Christiansen feature, Reststrahlen Bands, Transparency features) to the silica content of the product itself, no matter which crystalline phases are present within the rock. This finding is of pivotal importance since the determination of silica content is fundamental for characterizing volcanic products. On the other hand, investigations and analyses on VNIR spectra show that the interpretation within such is more complicated. Indeed, a small presence of Iron-bearing crystals can deeply influence the VNIR spectrum. However, some constraints can be built using empirical parameters and machine-learning approaches. All the spectra produced and published by our research group are or will be made available to everyone, open-source, within the platform hosted by ASI-SSDC (www.ssdc.asi.it/rockspectra/), making it possible for scientists from all over the world to integrate such data in other research or to directly compare planetary spectra to laboratory data.

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DaedalusCAM - An innovative exploration system for lunar lava tubes

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Keywords: lava tubes, moon, instrumentation.

The Moon's surface presents significant challenges for future exploration due to extreme conditions like radiation levels, temperature fluctuations, and meteorite impacts. One promising solution for future exploration, both scientifically and logistically involves using lunar lava tubes- natural tunnels formed by volcanic activity - as shelters for human habitation and operations. These structures could provide protection and may even contain water ice reserves, making them ideal for long-term lunar exploration and settlement. Recent radar evidence has confirmed the potential existence of lava tubes on the Moon (Carrer et al., 2024), fostering the need for more detailed exploration studies. To address this, the DaedalusCAM project aims to explore and map the interiors of lunar skylights (collapsed lava tube ceilings) and any underlying intact lava tubes. This is built upon the heritage of an innovative spherical robotic system called DAEDALUS, whose study was commissioned by ESA in a Concurrent Design Facility study upon a call for ideas for lava tubes exploration (Pozzobon et al., 2021; Borrmann et al., 2021). This mission concept foresees the descent into lunar skylights like the one in the Marius Hills region using a crane, equipped with two key payloads - a stereoscopic immersive camera system (PANCAM; Pernechele et al., 2018) and a pair of LIDARs. Upon an ASI funding, we were able to develop more the PANCAM concept into DaedalusCAM project. It consists of a system package of 4 bifocal panoramic lenses capturing both wide panoramic and high-resolution images with a hyper-hemispheric field of view (covering the entire surrounding space with redundancy) and equipped with navigation software. Its unique configuration of multiple cameras means each point on the lava tube walls is visible from at least two cameras, enabling stereoscopic 3D reconstruction. As DaedalusCAM descends will frame around 400 panoramic and scientific images to completely map the skylight and any accessible lava tube. The whole thermo-mechanic design is also being developed for the instrument package to account for launch vibrations and environmental conditions of the moon. The resulting large dataset must be processed by the DaedalusNAV software to generate an immersive, navigable 3D model of the explored environment. This involves correcting distortions, enhancing resolution, identifying stereoscopic tie points between images, and optimizing 3D point cloud reconstruction. The final 3D cave model will be viewable in an intuitive virtual reality interface, enabling interactive navigation and analysis. To validate the system, terrestrial lava tube analogs like those on Mt. Etna and Lanzarote are being studied, accounting for key differences from lunar environments including dimensions, genesis and illumination conditions. The DaedalusCAM project leverages an interdisciplinary team from Italian aerospace, astrophysics, and geosciences institutes to tackle this ambitious exploration vision. Successful mapping of lunar lava tube interiors would provide unprecedented scientific insights on the inception and development of these volcanic structures, the collapse mechanism, their extension and a peek on the thermal history of the moon, while demonstrating the feasibility of using these structures to support future human lunar exploration and habitation.

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Spectral and geological investigation of water ice in Oxo crater, Ceres: insights into ice origin and crater evolution

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Keywords: Ceres, geomorphology, spectroscopy.

This study employs integrated spectral and geological analyses for Oxo crater on Ceres, investigating the physical and compositional characteristics of its internal ice and the ice's role in the crater's geological evolution. Oxo, a geologically young crater (~9 km diameter) situated in Ceres' northern hemisphere (42.20°N, 359.75°E), has an estimated age of 1-10 million years (Combe et al., 2016). Utilizing observations from the VIR spectrometer (De Sanctis et al., 2011) on NASA's Dawn mission, we focused on the 1.0–4.2 μm infrared wavelength range where diagnostic water ice and carbonate absorptions are prominent.

Our methodology integrates focused spectroscopic analysis of VIR data with detailed geological mapping (QGIS environment) to investigate the interplay between water ice properties and the crater's geomorphological evolution, specifically focusing on features indicative of mass wasting. We classified illuminated pixels based on key absorption bands into four compositional classes: 1A (water ice and carbonates present), 1B (water ice present, carbonates weak), 1C (carbonates present, water ice absent), and 1D (neither feature distinct). This classification complements the mapping of specific compositional units across the crater floor and walls. Radiative transfer modeling (Hapke, 2012) was then applied to the ice-bearing classes (1A and 1B) using water ice optical constants (Mastrapa et al., 2009) to derive geologically relevant parameters: ice thermal state (temperature), granulometry, and abundance.

Spectral modeling yielded distinct physical characteristics for the ice-bearing pixel types, with areal mixing models providing the best fits. Class 1A deposits are consistent with T ≈ 110 K, 125 μm grain size, and ~1.4% abundance. Class 1B deposits are also consistent with a T ≈ 110 K, but are characterized by 105 μm grains and increased abundance (~2.0%). Ongoing geological analysis using QGIS and Dawn mission imagery seeks to understand the structural evolution of Oxo crater. We are mapping significant morphological features, particularly those related to potential mass wasting and volatile presence on the crater walls, floor, and surrounding area (Nathues et al., 2017). This geological context is being integrated with the spectral findings to assess how the properties and distribution of the identified ice-bearing pixels (1A and 1B) may have influenced slope stability and controlled the observed geomorphology.

This integrated analysis allows us to explore how the specific type and physical state of near- surface ice influence slope stability and contribute to the crater's modification. This work demonstrates the synergy between detailed spectral classification, radiative transfer modeling,and GIS-based mapping to yield crucial insights into active geological processes on planetary surfaces.

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CARE-ON Project – Assessing human-related uncertainties in planetary boulders identification

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Keywords: human detection error, moon surface analysis, citizen science.

While AI and neural network automation advance, expert visual validation remains critical in planetary image analysis, though it introduces uncertainty. Particularly, the absence of universally accepted identification criteria for planetary boulders and the risk of fatigue and personal biases may compromise counting reproducibility. The CARE-ON project (IGG-CNR) systematically evaluates human error in manual boulder identification, building on prior work such as Pajola et al. (2019) on lunar boulder distributions.

The study focuses on two sample areas in Mare Crisium (Moon), east of the Luna 24 landing site, near a 1-km size fresh Copernican crater. The project follows a structured approach:

Expert benchmarking with professional geologists to establish baseline identification variability;

Controlled boulders identification experiments, comparing results from students at planetary mapping courses (e.g., GMAP winter school, co-financed by University of Padova, Horizon 2020 programme and Europlanet Research Infrastructure) and amateur astronomers;

Workflow development integrating citizen science, while assessing data consistency.

Preliminary results highlight spatial and observer-dependent trends in feature identification. To provide reliable results, CARE-ON leverages collaborations between research and academic institutions with volunteer networks to ensure the development of robust detection protocols. By openly sharing guidelines and workflows, the project aims at enhancing reproducibility in planetary feature mapping and exploring the feasibility of sustained public participation in scientific research.

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Applying upscaled glacier structural analysis to the tectonics of icy satellites

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Keywords: icy satellites, tectonics, terrestrial analogs.

Multiscale analysis is a powerful approach for investigating the surfaces of Solar System bodies. It is particularly relevant for distant targets such as the icy satellites of the outer planets, whose exploration relies heavily on remote sensing and thus requires complementary analytical techniques. These satellites are primary targets of current missions: ESA's JUICE and NASA's Europa Clipper are both *en route* to the Jovian system to conduct detailed studies of these intriguing worlds. Advancing our understanding of these bodies is essential to achieving the scientific goals of these programs.

Most icy satellites feature an outer icy shell overlying a subsurface liquid water layer, considered a favorable environment for habitability. Driven mainly by tidal heating, this internal ocean causes deformation of the overlying brittle crust. As a result, satellites like Europa, Ganymede, and Enceladus are marked by kilometer-scale fractures/faults, typically formed under extensional and strike-slip stress regimes. Compressional tectonic structures are comparatively rare. These tectonic features are critical, potentially acting as conduits between the surface and the internal ocean.

This study explores how terrestrial analogs can inform our understanding of icy satellite tectonics. By collecting local-scale data from well-characterized terrestrial environments, specifically Argentinean glaciers, we apply scaling laws to interpret large-scale features observed remotely on icy satellites. We present results from glacial environments, comparing the structural configuration of terrestrial glaciers with strike-slip fault zones on icy satellites. In fact, glacier kinematics show strong analogies with the strike-slip deformation observed on these bodies. The structural patterns seen in glaciers provide a useful framework for inferring similar, otherwise hard-to-detect features on icy satellites. Using a multiscale approach that integrates local and regional datasets, we infer possible surface and subsurface structural configurations of icy crusts. Three-dimensional digital outcrop models were generated using Unmanned Aerial Vehicle imagery from Patagonian glaciers. Combined with field structural measurements and satellite data, these models enabled reconstruction of both surface and subsurface glacial structures. The insights gained were applied to interpreting regional-scale strike-slip zones on icy satellites.

This approach enhances our understanding of their structural evolution, from remote sensing surface features to deep crustal deformation, including compressional structures. The results will support scientific planning and target site selection for high-resolution imaging by JUICE mission.

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Comparison of alkali-activated regolith simulants: commercial formulations and Etna volcanic ashes for lunar construction

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Keywords: alkali-activated materials, lunar regolith simulants, In Situ Resource Utilization.

As space agencies advance plans for lunar settlements, balancing construction challenges with sustainability becomes crucial. This research optimizes alkali-activated lunar regolith formulations for *In Situ* Resource Utilization (ISRU), employing both commercial simulant and locally sourced materials. Sustainable construction materials producible on-site are paramount for reducing payload mass and enabling long-term lunar habitation, with alkali-activated materials representing a promising solution by eliminating the need to transport additional binders like Portland cement.

We initially implemented a Design of Experiments approach on commercial simulant formulations, analyzing parameters including alkaline activator amount, metakaolin addition, and curing temperature. Using this commercial simulant, we investigated two different alkaline activators (sodium alluminate and sodium silicate) and explored urea as an additive to modify rheological properties and enhance mechanical performance. This optimization identified promising formulations based on compressive strength and workability. Experimental procedures encompassed mechanical testing, rheological measurements, and microstructural characterization to understand reaction mechanisms.

Following optimization, we conducted a systematic investigation to identify potential lunar simulant sources within Italy, particularly from Mount Etna, using XRD and XRF analyses. These were evaluated against NASA simulant requirements, identifying materials analogous to Apollo 14 samples. The mineralogical and chemical composition of selected Etna basalts showed remarkable similarities to lunar regolith, particularly in silica content, aluminum oxide, and iron oxide percentages.

Results demonstrated that sodium silicate-based activators provided superior mechanical properties, while urea effectively improved workability without significant strength reduction. We applied our optimized formulations to Italian simulants, developing alkali-activated binders specifically tailored to lunar regolith characteristics. Comparative testing between commercial and Italian simulants revealed distinct advantages of the Etna-derived materials, including improved workability and comparable mechanical strength.

This alkaline activation approach offers significant advantages for lunar ISRU: minimal Earth-transported materials and potential radiation shielding properties. Additional benefits include compatibility with 3D printing technologies and excellent dimensional stability, crucial for structural applications in the harsh lunar environment.

This sequential approach, first optimizing with commercial simulants and then applying to Italian simulants from Etna, advances our understanding of alkali-activated materials for lunar construction, paving the way for sustainable and efficient lunar settlements. Our findings demonstrate that locally-sourced simulants can match and potentially exceed the performance of commercial alternatives, offering a pathway to more sustainable research in space construction materials.

The magma ocean of Mercury: Insights into the early evolution of the innermost planet

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Keywords: Mercury, magma ocean, experimental petrology

Planet Mercury has unique chemical characteristics and physical properties among the terrestrial bodies (Namur & Charlier, 2019). In particular, Mercury is the smallest terrestrial planet in our Solar System and is characterized by a large metallic core. During accretion, the heat liberated from early large accretional impacts, core-mantle differentiation, and radiogenic decay was sufficient to melt Mercury. This early stage, referred to as "Magma Ocean", has been first invoked for the Moon and is thought to have occurred in most terrestrial planets. As the silicate and metal portions separated, the progressive crystallization of the silicate part resulted in the formation of the primordial mantle. What occurs during this critical period of differentiation sets the stage for all subsequent events that shaped Mercury as we see it today. This includes mantle remelting and the production of a secondary magmatic crust, as well as the stability and storage of volatile elements that are crucial for planetary dynamics and potentially building of an atmosphere. The geochemical data returned by NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft revealed an unusually high concentration of sulfur of surface volcanic units coupled with the paucity of iron. This pointed to highly reduced conditions (low oxygen availability) of formation of surface lavas. Sulfur is therefore thought to be a major mantle volatile, with profound implications for melting temperatures, phase equilibria and, as a consequence, the vertical structure of the mantle (Saracino et al., 2025). Our goal is to investigate the structure of the primordial mantle of Mercury as a direct result of the crystallization of its magma ocean, thus providing a revised standard model for the evolution of the planet in its early history. Laboratory experiments were performed on Mercury-like mantle compositions, at high temperature and different pressures, in conditions of low oxygen fugacity and sulfur saturation. Experimental results (phase equilibria, major element distribution) were then combined with thermodynamical modelling to simulate the fractional crystallization of Mercury's magma ocean, in order to reconstruct the stratigraphic sequence of Mercury's primordial mantle. Preliminary results show that orthopyroxene is the main silicate mineral making up the primordial mantle of Mercury, and that the presence of sulfur in the magma stabilizes orthopyroxene over olivine. We also show that more evolved products are only limited to the mantle-crust interface, with clinopyroxene and plagioclase crystallization being delayed in the presence of sulfur. Moreover, we show that sulfide minerals may segregate from the magma ocean, and their abundance will depend on the initial S content of the magma ocean. Our results have major implications for the early evolution of Mercury, mantle melting and the formation of the volcanic crust.

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Experimental petrology approaches to lunar volcanism: the case study of Lunar Sinuous Rilles (LSR)

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Keywords: Moon, experimental petrology, planetology.

The Moon was shaped in time by many different processes, some of which have left evident features on the Moon's surface, such as, for example, impact craters, *mare* basins and lunar sinuous rilles (LSR). These processes also influenced the distribution of minerals and elements on the lunar surface, making their study essential for future lunar exploration and *in situ* resource utilization. Being very common the acquisition and interpretation of spectral data to study planetary surfaces, one of the main objectives of this project is to create a solid reference database of silicate glasses with different moon-like compositions, to support the future efforts of interpretations of the Moon's surface.

Thus, the first step has been to create lab-made igneous analogues with the composition of four different lunar products: Apollo 11 mare high-Ti basalt, renamed MB; Apollo 15 low-Ti basalt, LTB; Apollo 15 KREEP basalt, KB; Apollo 15 Green Glass, GG. These compositions were taken from Taylor (1982). The preparation of the synthetic silicate glasses has been made starting from the mixing of previously weighted oxides, then melted in a Nabertherm furnace at 1400 °C, with an average time of high-temperature homogenization of 3-4 hours for each sample. Every sample has been grinded and melted twice, to obtain better homogenization. However, the MB sample showed signs of oxidation and crystallization, which will be investigated further. After the production of the four analogues, 10 grams of each sample was grinded and sifted, establishing 5 different granulometric classes (0-38 μm, 38-63 μm, 63-106 μm, 106-150 μm, > 150 μm). The first four of these classes (taken for each analogue, for a total of 16 different samples) were analyzed with the FTIR spectroscopy (Bruker). After the spectral characterization, the four samples were melted in a GERO furnace at 1600 °C to measure their viscosities with a rotating viscometer (an Anton Paar Rheometer with a platinum spindle).

Taylor S.R. (1982) - Planetary science: A lunar perspective. Lunar and Planetary Institute, Houston, 481 p.

Handheld Laser-Induced Breakdown Spectroscopy (hLIBS), an alternative technique for chemical classification of iron meteorites

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Keywords: handheld LIBS, iron meteorites, composition.

The bulk characterization and classification of iron meteorites mostly rely on their elemental composition data acquired by inductively coupled plasma-mass spectrometry (ICP-MS), instrumental and radiochemical neutron activation analysis (respectively INAA and RNAA) or laser ablation ICP-MS (LA-ICP-MS). Although these techniques have allowed the acquisition of a very large set of high-quality data that are the foundations of the current understanding of iron meteorites, they are time-consuming and of limited availability and access. Portable/handheld field instruments allow dynamic sampling, thus encouraging field geologists to expand their investigation and map areas where anomalies are observed, avoiding to depend on laboratory data. In explorative environmental projects, the benefit of this approach can be of weeks or even months of time saving for logistics and field campaigns, but also for costs of the subsequent laboratory work. In this context, the use of *in-situ* analytical tools is becoming increasingly common, as it facilitates a quick initial bulk chemical analysis, identification and classification. In this work, a handheld laser-induced breakdown spectroscopy (hLIBS) instrument has been used to identify the qualitative and quantitative composition of a suite of iron meteorite samples representative of different chemical and structural classes by analyzing the spectra released from the plasma formed by the laser impact. The LIBS technique offers several advantages, which include the large range of potentially detectable and quantitatively measurable major, minor and trace elements, ease-of-use, no need of reactants and sample pretreatment/preparation, almost no risk of sample contamination and environmental interferences, and micro-destructivity as the removal of minimal portion of the sample after each laser pulse produces a small crater on the sample surface (Harmon & Senesi, 2021; Senesi et al., 2021). Furthermore, the quick screening of samples with achievement of their elemental composition directly in the field allows to rapidly distinguish between terrestrial rocks and dubious meteorites and assume decisions. To evaluate the analytical performance of hLIBS, data acquired by this technique were compared with those available in the current literature. A good agreement was achieved between hLIBS and reference data in the quantitative estimate of the elements Fe, Ni, Co and Cu, thus the proposed protocol could be used directly in the field to measure new findings of iron meteorites.

Harmon R.S. & Senesi G.S. (2021) - Laser-Induced Breakdown Spectroscopy – A geochemical tool for the 21st century. Appl. Geochem., 128, 104929, https://doi.org/10.1016/j.apgeochem.2021.104929.

Senesi G.S. et al. (2021) - Field-portable and handheld laser-induced breakdown spectroscopy: Historical review, current status and future prospects. Spectrochim. Acta Part B, At. Spectrosc., 175, 106013, https://doi.org/10.1016/j.sab.2020.106013.

Petrography of Martian meteorite Northeast Africa (NEA) 053

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Keywords: petrography, martian meteorite, NEA 053.

The study of Martian meteorites offers critical insights into Mars' magmatic and volcanic processes (e.g., Udry et al., 2020). Shergottites, which account for about 90% of known Martian meteorites, are mantle-derived rocks that crystallized either through extrusive volcanic eruptions or intrusive processes within the Martian crust (Shehaj et al., 2025). Here, we report the petrography of Northeast Africa (NEA) 053, a pyroxene- and olivine-phyric shergottite that exhibits an igneous bimodal grain-size texture, unusual for a Martian meteorite. To investigate this texture, a centimeter-sized fragment of NEA 053 was embedded in epoxy, polished, and analyzed using scanning electron microscopy (SEM) and electron microprobe analysis (EMPA).

The sample exhibits a porphyritic texture, with olivine (Ol) and pyroxene (Px) phenocrysts embedded in a fine-grained matrix composed of lath-like maskelynite (shocked feldspar) and pyroxene.

Pyroxene phenocrysts are characterized by grain-size layering between fine- and coarse-grained texture. In both portions, they exhibit similar zoning patterns and compositions, starting with Mg-rich pigeonite ($En_{63-65}Fs_{25-26}Wo_{10-11}$), mantled by augite ($En_{47-51}Fs_{25-26}Wo_{25-27}$), and rimmed by Fe-rich pigeonite ($En_{39-45}Fs_{41-48}Wo_{13-15}$), similar to the zoning pattern observed in NWA 16788 (Shehaj et al., 2025). In the fine-grained portion, pyroxene crystals range from ~30 µm to 1.7 mm (average ~270 µm), and in the coarse-grained portion from ~30 µm to 2.2 mm (average ~500 µm).

Olivine phenocrysts are uniformly distributed throughout the investigated section. They occur as euhedral to subhedral crystals, ranging in size from approximately 40 µm to 1.8 mm (average ~350 µm). They commonly display normal zoning, with Mg-rich cores ($Fo_{62–68}$) transitioning to Fe-rich rims ($Fo_{53–56}$).

The matrix consists of pyroxene and maskelynite (Msk), exhibiting a lath-like texture and uniform distribution. The pyroxene shows limited compositional zoning ($En_{39–43}Fs4_{2–49}Wo_{12–15}$), while the maskelynite displays a homogeneous composition ($An_{47}Ab_{50}Or_3$).

Accessory phases are equally distributed in both textural domains, comprising approximately 2 vol.% of the sample, and include Fe-Ti-Cr oxides, ilmenite, Fe-sulfide, phosphates.

Textural analyses reveal that the modal abundances of pyroxene, olivine, and maskelynite are comparable between the fine-grained ($Px_{53}Msk_{24}Ol_{21}$) and the coarse-grained ($Px_{54}Msk_{26}Ol_{17}$) portions.

We interpret the grain-size layering between fine- and coarse-grained as evidence of a portion of crystal mush. This suggests that Martian magmatic activity exhibited rheological properties and dynamics similar to those of Earth's magmatic systems.

Shehaj X. et al. (2025) - Northwest Africa (NWA) 16788: A New Olivine Microgabbroic Shergottite. Insights Into Martian Magmatism From the Largest Individual Meteorite From Mars. J. Geophys. Res.: Planets, paper #2024JE008885.

Udry A. et al. (2020) - What Martian meteorites reveal about the interior and surface of Mars. J. Geophys. Res.: Planets, e2020JE006523, https://doi.org/10.1029/2020JE006523.

An oxidised upper lunar magma ocean

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Keywords: Moon, redox, anorthosite.

The Moon, which likely formed in the aftermath of a giant impact that led to a lunar magma ocean, is thought to be reducing. Phase assemblages in lunar mare basalts record an oxygen fugacity, f_{O2}, of ~1 log unit below the iron-wüstite buffer (Sato, 1976), similar to that inferred for core formation on the Moon (Sossi et al., 2025). However, mare basalts define ages younger than 3.9 Ga, and are therefore not directly representative of the composition of the magma ocean.

Here, we report Fe K-edge X-Ray Absorption Near-Edge Structure (XANES) spectra collected on 10 ferroan anorthosite (FAN) Apollo samples from the ~4.35 Ga lunar highlands (Borg & Carlson, 2022). Based on an independent calibration of synthetically grown anorthitic plagioclase in equilibrium with silicate melts at known f_{O2} (Ofierska et al., 2025), we quantify the iron contents and $Fe^{3+}/[Fe^{3+} + Fe^{2+}]$ ratios of plagioclase contained in FANs in order to determine the apparent f_{O2} under which they last equilibrated.

We find that the FeO contents of anorthitic plagioclase in FAN are too low to have been in equilibrium with a magma produced by extensive fractional crystallisation of the lunar magma ocean. The $Fe^{3+}/[Fe^{3+} + Fe^{2+}]$ ratios defined by FAN plagioclase are homogeneous across the 10 samples, ~0.4, corresponding to oxygen fugacities ~1 log unit above the fayalite-magnetite-quartz buffer. These apparent f_{O2}s are at least four log10-units more oxidising than those inferred from mare basalts. We discuss the implications of these results for the composition of an early atmosphere in equilibrium with an upper lunar magma ocean.

Borg L.E. & Carlson R.W. (2023) - The Evolving Chronology of Moon Formation. Ann. Rev. Earth Planet. Sci., 51, 25-52, https://doi.org/10.1146/annurev-earth-031621-060538.

Ofierska W.L. et al. (2025) - Calibration of the relationship between oxygen fugacity and the oxidation state of iron in anorthitic plagioclase. Chem. Geol., 122814, https://doi.org/10.1016/j.chemgeo.2025.122814.

Sato M. (1976) - Oxygen Fugacity Values of Some Apollo 16 and 17 Rocks. Lunar Planet. Sci. Conf., 758.

Sossi P.A. et al. (2025) - Composition, Structure and Origin of the Moon. Treatise on Geochemistry, 3rd Ed., 417-479, https://doi.org/10.1016/B978-0-323-99762-1.00138-8.

Stishovite in a Muonionalusta iron meteorite: occurrence, possible formation pathways and constraints on impact conditions

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Keywords: stishovite, iron meteorite, impact event.

Stishovite, a rare high-pressure polymorph of silica (SiO_2), can provide crucial insights into extreme geological environments and high-pressure metamorphic conditions. Since its initial discovery at the Barringer Crater, stishovite has been identified in various impact-related settings, including terrestrial impact craters, meteorites from Mars, the Moon, and Vesta, as well as lunar-returned samples. Terrestrial metamorphic occurrences, such as in granulite, have also been reported (Thomas et al., 2022).

Stishovite in iron meteorites was first identified in the Muonionalusta iron meteorite (group IVA) from Sweden (Holtstam et al., 2003) and later in the Tishomingo meteorite (Corrigan et al., 2005). However, previous studies were limited to spectroscopic and diffraction analyses, leaving the occurrence and origin of stishovite unclear.

In this study, a stishovite-rich melt vein was found in Muonionalusta meteorite, and detailed nano- to submicron-scale characterization was conducted using Scanning Electron Microscopy and Focus Ion Beam – Transmission Electron Microscopy. We identified stishovite occurring as nanocrystals in two forms: nanocrystals within SiO_2-rich clasts and small aggregates encased in SiO_2 glass within the cement. The SiO_2-rich clasts are typically a few micrometers in size and contain randomly oriented stishovite nanocrystals with grain sizes ranging from 30 to 200 nm, embedded in an amorphous SiO_2 matrix. In the cemented regions, SiO_2-rich clusters (100–400 nm) coexist with recrystallized troilite, displaying an encapsulated structure with an amorphous SiO_2 outer layer and crystalline stishovite cores.

These distinct morphologies possibly suggest two formation pathways: solid-solid transformation (Otzen et al., 2024) for the clast-hosted nanocrystals and liquid-solid crystallization for the aggregates in the cement. If the cemented regions indeed originated from melt crystallization, it suggests that the impact event may have reached pressures above 13 GPa and temperatures exceeding 3100 K. This study provides new temperature and pressure constraints for the catastrophic disruption of a metallic asteroid based on high-pressure mineral phases, offering insights into the impact history of iron meteorites.

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Holtstam D. et al. (2003) - First discovery of stishovite in an iron meteorite. Meteorit. Planet. Sci., 38, 1579-1583, https://doi.org/10.1111/j.1945-5100.2003.tb00002.x.

Otzen C. et al. (2024) - A new mechanism for stishovite formation during rapid compression of quartz and implications for asteroid impacts. J. Geophys. Res. Planets, 129, e2023JE008126, https://doi.org/10.1029/2023JE008126.

Thomas R. et al. (2022) - Discovery of stishovite in the prismatine-bearing granulite from Waldheim, Germany: A possible role of supercritical fluids of ultrahigh-pressure origin. Geosciences, 12, 196, https://doi.org/10.3390/geosciences12050196.

Characterization and feasibility of lunar landing sites: the Ingenii basin case

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Keywords: lunar landing sites, Ingenii basin, Moon.

The renewed interest in the exploration of the Moon, both human and robotic, and the technological advancement made it more feasible to look at sites previously underrated for the paucity of high-resolution data available (e.g. polar regions) and the challenges in communication (e.g. far side), accessibility and trafficability (e.g. underground cave systems). Being characterized by a smooth basaltic infilling, optimal for landing and roving, the far side Ingenii basin (33.25°S, 164.83°E) represents a high-profile objective for the unique presence of both extensive and complex swirls, namely features related to crustal magnetic anomalies (Garrick-Bethell et al., 2011), and a pit with overhanging roof possibly giving access to a lava tube. In this study, we characterized the area surrounding the Mare Ingenii Pit (MIP) and performed a feasibility study for a robotic mission with a rover-hopper by considering traverses of varying lengths, all providing for a hopping phase inside the pit, and simulating the environmental conditions along their paths. More in detail, we used the Lunar Reconnaissance Orbiter (LRO) Wide Angle Camera (WAC) mosaic (up to 100 m/px) (Robinson et al., 2010) for a contextual interpretation of the area together with LRO Narrow Angle Camera (NAC) images (up to 0.5 m/px) (Robinson et al., 2010) for a detailed characterization of the area surrounding the MIP. The Lunar Orbiter Laser Altimeter (LOLA) and Kaguya Terrain Camera merged Digital Elevation Model (DEM) provide the most up-to-date surface height and slope information (vertical accuracy of 3-4 m) (Barker et al., 2016) and a NAC-derived Digital Terrain Model (DTM) provides the best available elevation data for the area surrounding the pit. We quantitatively assessed the topographical characteristics of the surface within a reasonable distance from the MIP for the positioning of landing ellipses (1500 and 500 m in diameter), and automatically detected boulders > 1 m using a machine learning algorithm and NAC imagery (Prieur et al., 2023). We then planned short (up to 5 km), intermediate-length (up to 10 km) and long (up to 15 km) traverses and evaluated slope and elevation variations along the paths taking into account a typical slope tolerance of maximum 15°. Finally, we used an interactive tool provided by LROC Quickmap to perform simulations of the environmental conditions along each traverse path and identify a mission operating window based on illumination and temperature conditions over a lunar day. A lunar landing candidate site located on the far side sure entails a major effort in communicating with Earth, however, the scientific relevance and peculiarity of Ingenii basin and its optimal topographical characteristics make it a site to be considered for future exploration.

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Garrick-Bethell I. et al. (2011) - Spectral properties, magnetic fields, and dust transport at lunar swirls. Icarus, 212, 408-492, https://doi.org/10.1016/j.icarus.2010.11.036.

Prieur N.C. et al. (2023) - Automatic characterization of boulders on planetary Surfaces from high-resolution satellite images. JGR, 128, e2023JE008013, https://doi.org/10.1029/2023JE008013.

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Introducing the open-source PANCO suite for alignment and pansharpening of multi and hyperspectral images

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Keywords: remote sensing, imaging, spectrometry.

Introduction: Multi- and hyperspectral imaging is a fundamental tool in modern geology, notably in planetary science, providing the foundation for many morphological and compositional analyses. Despite technological improvements, several physical limitations force even the most modern sensors into a constant trade-off between spatial and spectral resolution. Pansharpening represents a research field branching from remote sensing and data fusion ambits that aim at the mutual enhancement of multi or hyperspectral data with a broadband higher spatial resolution panchromatic image. To date, the pansharpening family consists of numerous approaches and applications.

Based on the latest developments in the field, the PANCO (PANsharpening and CO-registration) suite aims to provide a suite of open-source tools that enable the use of various pansharpening algorithms and prepare images for its implementation through simplified automatic co-registration algorithms (Tullo et al., 2024). This could greatly simplify the use of pansharpening in remote sensing studies, even extending its use to images taken not only from the same platform/orbiter but also to datasets from multiple missions that otherwise lack preliminary co-registration and orthorectification.

Image alignment: The co-alignment of georeferenced images in GIS is typically performed manually, requiring the definition of multiple Ground Control Points (GCPs) between the two images. This process can be time-consuming and prone to human error. To streamline this task and reduce the likelihood of mistakes, an automated pre-alignment technique has been developed and implemented in PANCO. This method utilizes the SIFT (Scale-Invariant Feature Transform) computer vision algorithm, which can identify significantly more tie points than a typical human operator. As a result, the viewing geometries of the images can be harmonized with minimal or no risk of distortion, leaving the operator with only the need for a final local refinement step. The application of this procedure to various test datasets has demonstrated average accuracy levels below one pixel of error.

Pansharpening algorithms and validation: There are currently more than ten pansharpening methods and variants available in PANCO. These include algorithms capable of processing entire hyperspectral cubes, such as the Gram-Schmidt Adaptive (GSA) method (Aiazzi et al., 2007) and the recent Band-Dependent Spatial Detail with Physical Constraints (BDSD-PC) method (Vivone, 2019). Validation of these tools is underway through a series of studies initiated by Tullo et al. (2024), which focus on their application in real-world contexts. One such application involves studying the surface of Mars using CaSSIS data from the ExoMars Trace Gas Orbiter (TGO) mission, as well as HiRISE and CRISM data from the Mars Reconnaissance Orbiter (MRO) mission.

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S6.

From deep feeding systems to eruptive processes: petrologic tools for probing volcanoes

CONVENERS AND CHAIRPERSONS

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Magma storage and plumbing system evolution at Mount Melbourne (Northern Victoria Land, Antarctica)

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Keywords: Mount Melbourne, Antarctica, machine learning.

Mount Melbourne, a large Quaternary stratovolcano in Northern Victoria Land, is one of the few volcanoes on the Antarctic plate with a proven potential for Plinian-scale explosive eruptions (Giordano et al., 2012). Its complex evolution, ranging from early subglacial basaltic activity to recent trachytic and rhyolitic pumice falls, makes it an ideal target for investigating long-lived alkaline magmatic systems in rift-related, glaciated settings.

ue to their remoteness and limited monitoring, the eruptive behaviour and risk potential of Antarctica's volcanoes remain poorly understood. Recent modelling studies suggest that ash from Antarctic eruptions could disperse over vast areas and potentially encircle the globe, intersecting commercial flight routes and posing significant risks to global aviation safety (Geyer et al., 2017). This underscores the urgent need to understand the magmatic systems of Antarctic volcanoes and their potential to produce hazardous, large-scale explosive eruptions.

In this study, we used an integrated petrological and machine learning approach to investigate the architecture and magmatic evolution of Mount Melbourne. We present new major and trace element data along with high-resolution chemical mapping of the crystal cargo integrated with machine learning thermobarometry and clustering techniques. This contribution aims to reconstruct crystallisation conditions and reservoir dynamics over time and improve our understanding of subglacial volcanic hazards.

This research highlights Mount Melbourne's significance as a natural laboratory for exploring explosive intra-plate volcanism in polar regions. It demonstrates how advanced petrological tools can help decipher the deep-to-surface processes controlling volcanic behaviour.

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Exploring architecture and dynamics of caldera systems during volcanic unrest: The example of the Campi Flegrei caldera (Italy)

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Keywords: Campi Flegrei, caldera, volcanic unrest.

Large silicic calderas feed the most explosive and catastrophic eruptions on Earth. These volcanic systems may experience extended periods of unrest originated by magmatic processes (movements of magma), non-magmatic sources (e.g., hydrothermal or tectonic processes), or a combination of causes. An intriguing case is the densely populated caldera of Campi Flegrei (CFc), southern Italy. Since 2005, the caldera is in a new phase of an unrest that has persisted intermittently for several decades (main crises during 1950-1952, 1970–1972, and 1982–1984), characterized by increasing ground uplift, seismicity and hydrothermal activity. In this study, we conducted a multidisciplinary investigation aimed at assembling a broader and clearer picture of the CFc system and dynamics. We performed a multiscale analysis, integrating results from 4D X-ray microtomographies at the well core-scale with a 3D high-resolution seismic tomography at the crustal-scale, to accurately reconstruct anatomy and properties of the shallow (0-4 km depth) volcanic structure, where deformation source, seismogenic volume and hydrothermal system are located. To elucidate the context of our most notable observations, we performed numerical simulations of magmatic dike ascent from an 8 km-deep reservoir. These simulations track the dykes as they rise into the upper crust above 4 km depth, where our tomographic study is focused and where the carbonate basement transitions to the overlying low-density, caldera-filling tuffs. Our study reveals that crustal rocks progressively strengthen and compact with depth into brittle, stiff, tough, and low-permeability layers down to ~2-2.5 km. Below this depth, however, there is an unexpected mechanical deterioration of the crustal layers, which around depths of 3-4 km become porous, permeable, and less resistant. This weak zone acts as a structural trap for magmatic fluids ascending from depth, leading them to accumulate and develop overpressure, which can in turn lead to deformation and seismic activity. We propose that similar weak zones acting as fluid traps may be a common feature of calderas. These zones would form through the repeated emplacement of dykes over the caldera's history at depths where the stress field below the caldera floor favors dike arrest, as indicated by our propagation simulations. Within these mechanically weak volumes, varying amounts of gas, magma, or both can accumulate over time, giving rise to the diverse unrest behaviors observed across caldera systems.

The magma plumbing system of Large Igneous Provinces: Insights from glomerocrysts and melt inclusions

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Keywords: Central Atlantic Magmatic Province (CAMP), Deccan Traps (Deccan), oxygen isotopes.

The magma plumbing system of Large Igneous Provinces (LIPs) is still poorly understood. Among the most voluminous LIPs, the end-Triassic Central Atlantic Magmatic Province (CAMP; Marzoli et al., 1999) and the end-Cretaceous Deccan Traps (Deccan; Sprain et al., 2019) coincided in time with two of the most catastrophic biotic crises from Earth's past. In order to constrain the architecture of their magma plumbing system, glomerocrysts containing abundant bubble-bearing melt inclusions from basaltic lava flows of both CAMP and Deccan were investigated via a multi-analytical approach. Confocal Raman microspectroscopy was employed for volatile species within bubbles, electron microprobe for major element compositions, secondary ion mass spectrometry for oxygen isotope compositions, Synchrotron X-ray microtomography and optical microscopy for microstructural analysis. The analysed glomerocrysts, dominated by augitic clinopyroxenes, represent portions of crystal mushes. The analysed melt inclusions, consisting of an intermediate to felsic composition glass and CO_2-bearing bubbles, represent relics of interstitial melts and fluids entrapped during the evolution of these crystal mushes. The different volume proportions of bubbles within melt inclusions indicate heterogeneous entrapment, implying that melts were entrapped after volatile exsolution. The reconstructed CO_2 concentration in CAMP and Deccan melts was at least 0.3 wt.% (Capriolo et al., 2024), consistent with a maximum entrapment pressure of about 0.5 GPa at CO_2–H_2O fluid-saturated conditions. The MgO-rich compositions of clinopyroxene in glomerocrysts and whole rocks are in contrast with the SiO_2-rich compositions of (trachy-) andesitic to rhyolitic glass in melt inclusions, unveiling disequilibrium conditions, as supported by thermodynamic and geochemical modelling. Oxygen isotope compositions of clinopyroxene in glomerocrysts range from +3.9 (± 0.3) to +5.8 (± 0.3) ‰ (Capriolo et al., 2024), implying that glomerocrysts crystallized from mafic melts with mantle-like to slightly low $\delta^{18}O$ values. However, oxygen isotope compositions of glass in melt inclusions range from +5.5 (± 0.4) to +22.1 (± 0.4) ‰ (Capriolo et al., 2024), implying that melt inclusions entrapped distinct, intermediate to felsic melts with mantle-like to extremely high $\delta^{18}O$ values, which may depend on variable degrees of crustal assimilation and partial mixing in an open system. Hence, oxygen isotope compositions of glass in melt inclusions also suggest that the CO_2 within their coexisting bubbles likely derived partly from the mantle and partly from assimilated crustal materials. In conclusion, geochemical data and microstructural observations reveal the presence of multiphase (i.e., solid + liquid + gas phases) crystal mushes throughout the magma plumbing system of both CAMP and Deccan.

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Sprain C.J. et al. (2019) - The eruptive tempo of Deccan volcanism in relation to the Cretaceous–Paleogene boundary.. Science, 363(6429), 866-870, https://doi.org/10.1126/science.aav1446.

Unravelling the temporal evolution of magmatic processes under La Palma, Canary Islands

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Keywords: geochemistry, petrology, volcanology.

The dynamics of magma plumbing systems regulate not only the timing, composition and style of volcanic eruptions, but also underlying magmatic processes such as magma recharge, mixing, and crystal mobilization. In this contribution, we investigate the temporal evolution of magmatic processes beneath La Palma, Canary Islands, by targeting three eruptions that occurred in historical time: the 1712 El Charco, the 1971 Teneguía, and the 2021 Tajogaite eruption. These three eruptions are all characterized by the involvement of two distinct magmas: an amphibole- and pyroxene-dominated tephrite, and an olivine- and pyroxene-dominated basanite. Specifically, we focus on the major and trace element analysis of clinopyroxene crystals in lava samples, coupled with quantitative trace element maps and textural data, as their chemical composition and zoning patterns can preserve detailed records of magmatic evolution. Across all studied eruptions, clinopyroxene cores show a consistently broader range of Mg# values than rims and microlites, the latter two being in major element equilibrium with their carrier melts. Clinopyroxene – melt barometry of cores and rims shows temporally consistent crystallization depths ~20-26 km, in agreement with the location of the deep seismicity recorded prior to the 2021 Tajogaite eruption. Cluster analysis of clinopyroxene trace element data and quantitative chemical maps reveals temporally consistent features in all samples: (1) compositionally and texturally complex clinopyroxene cores, characterized by patchy domains and variable trace element signatures, and (2) Cr- and Sc-rich rims surrounding the crystals. These features point to the presence of a chemically heterogeneous mush system beneath La Palma, with mafic recharge and subsequent mush disaggregation acting as the primary eruption trigger. Additionally, clinopyroxene and matrix trace element compositions are similar across the targeted eruptions and align along a common trend controlled by fractional crystallization, suggesting that the magmas were derived from a shared mantle source feeding all three eruptions.

The glomerocrysts record for magma differentiation in a mush-dominated trans-crustal plumbing system: the case of Marsili volcano

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Keywords: Marsili volcano, mush, glomerocrysts.

Located in the Tyrrhenian Sea, the Marsili Volcano (MV) is a seamount that formed within a back-arc setting. Aiming to define the complexity of its trans-crustal plumbing system, we investigated the compositional and textural variability of glomerocrysts found within basaltic to andesitic lavas collected from three different sectors of the volcano (northern, axial, and lateral). The studied glomerocrysts are made of early-formed igneous mineral phases (i.e., olivine, clinopyroxene, plagioclase) and exhibit textural and compositional features indicative of a cumulate crystal mush origin. Lavas erupted from the northern sector are only basalts and host glomerocrysts more primitive in character compared to those found in basalts erupted from the lateral and axial sectors. Basaltic andesites were also erupted at these sectors, hosting glomerocrysts with a broad variability in terms of mineral assemblage and chemistry. Thermobarometric calculations performed on the mineral phases of the glomerocrysts indicate that they are fragments of a petrologically heterogeneous, 10-12 km thick trans-crustal mush system underlying the MV. In detail, glomerocrysts hosted in basalt and basaltic andesite lavas erupted at the axial sector originate from a middle to lower mush zone (200–450 MPa), with temperatures ranging from 1130 to 1180 °C. A similar temperature range is recorded by the mush zone sourcing the glomerocrysts hosted in the northern sector basalts and confined to a narrow middle crust level (200-300 MPa). Glomerocrysts found in basalt and basaltic andesite lavas from the lateral sector appear to derive from a similar middle to upper crustal mush zone (100–300 MPa) and record lower temperatures (1075–1125 °C). These data, integrated with the results of cluster analysis carried out with major elements for every phase contained in each glomerocryst type, allows us to explore the relationship of the investigated glomerocrysts with the evolutionary path of the MV lavas.

Impact of cooling rate on rheology and emplacement dynamics of basaltic lavas: insights from the January 2024 Sundhnúksgígar eruption (Iceland)

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Keywords: lava flow, rheology of silicate melts.

The 2023-2024 eruptions at Sundhnúksgígar in Iceland produced tholeiitic basaltic lavas that traveled at high velocities, affecting vast areas. Under such conditions, disequilibrium crystallization can play a fundamental role in modulating the lava flow dynamics and inundation capacity. To investigate this phenomenon, we carried out a comprehensive rheological characterization of the Sundhnúksgígar basalt, analyzing both the liquid phase and the crystal-bearing suspensions under disequilibrium conditions (cooling rates ranging from 0.1 to 10 °C/min) and near-equilibrium conditions (at fixed temperatures between 1242 and 1180 °C). Our results show that the cooling rate critically influences the extent and timescale of disequilibrium crystallization, thereby shaping the rheological evolution of the melt, leading to distinct deformation response of the crystal-bearing magmatic suspension. Compared to other basalts erupted worldwide, the Sundhnúksgígar melt exhibits two main features: i) an exceptionally low rate of viscosity increase induced by crystallization and ii) the ability to crystallize even at the highest cooling rates applied during the experiments. These characteristics may contribute to enhancing the efficiency of external crust formation, limiting heat loss from the inner portion of the lava flow, which consequently cools more slowly. Thermal insulation effects reduce the rate of viscosity increase during lava emplacement, a key factor in determining lava flow inundation potential. Our findings underscore the critical role of disequilibrium crystallization in governing the rheological evolution and emplacement dynamics of basaltic lavas, offering new insights into lava flow behavior.

Coexisting high- and low-K magmas in the ancient, pre-BLT activity (> 350 ka) of the Roccamonfina volcano (southern Italy)

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Keywords: Roccamonfina, Italian potassic magmas, geochemistry.

Roccamonfina is an extinct stratovolcano of the Italian peninsula where leucite-bearing ultrapotassic products are generally considered to predate leucite-free shoshonitic products. This relationship is largely based on studies conducted on lavas, while pyroclastic successions have been generally overlooked due to their poor preservation. Here we report a detailed petrological investigation of both lavas and juvenile pyroclastic products of the oldest stages of volcanic activity (i.e., > 350 ka) cropping out on the eastern side of the edifice. The lavas have mainly vesicular, fine- to coarse-grained, porphyritic texture with hypocrystalline, hypohyaline, and holocrystalline groundmass. Clinopyroxene, leucite, plagioclase and opaque minerals are ubiquitously present in the least evolved samples, while the most evolved ones feature alkali feldspar and leucite as the main phenocryst phases. Compositions range from potassium-rich, silica-undersaturated tephrites to strong evolved phonolites. Most of the juvenile components of the pyroclastic deposits instead are crystal-poor pumice clasts with few clinopyroxene and sanidine microphenocrysts set into a brownish, glassy groundmass with sparse, variably altered to fresh leucite crystals. A smaller number of clasts are relatively crystal-rich and feature clinopyroxene, altered leucite and biotite phenocrysts plus variable amounts of sanidine and plagioclase, depending on the rock composition. Whole-rock compositions range from tephrite to phonolite, whereas glass compositions range from phonotephrite to phonolite. Interestingly, leucite-free juvenile clasts were also observed. These are typically crystal-poor, featuring only rare alkali feldspar and clinopyroxene phenocrysts set into a trachytic groundmass. Whole-rock and glass compositions are trachytic, in line with that of the most recent shoshonitic products. Surprisingly, both leucite-bearing and leucite-free samples display comparable ranges of Sr (0.70900-0.71019 vs. 0.70872-0.70913) and Nd (0.51211-0.51220 vs. 0.51220-0.51224) isotope ratios. These preliminary results suggest that the ancient Roccamonfina activity was significantly more complex than previously thought, featuring at least two different magma series emplaced simultaneously and possibly deriving from similar mantle sources.

Deciphering magma ascent P-T path of Mt. Etna flank eruptions: new insights from crystal-melt thermobarometry and amphibole-rich cumulates

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Keywords: feeding system, thermobarometry, fractional crystallization.

Mt. Etna features a plumbing system characterized by a central open-conduit, culminating with the summit craters, three rift-related lateral systems (S-Rift, NE Rift and W Rift) and the eccentric feeding system, characterized by disperse monogenetic cones. In the last twenty years, most the eruptive activity occurred at the summit central craters and by consequence most of the recent studies focused on the parametrization of the central open-conduit system. However, rift-related events are potentially more dangerous since they are often accompanied by energetic precursor seismicity and increased probability of lava effusion at low altitude, where infrastructures are concentrated. Previous petrologic studies of the last rift-related eruptions of 2001 (S-Rift) and 2002-2003 (S and NE-Rifts) highlighted the importance of mixing between the magma from the main central conduit and magma batches formed after lateral draining from the central conduit or constituted by magmatic input which rose independently through the rift systems (Viccaro et al., 2005; Giacomoni et al., 2012). Amphibole phenocrysts were found in 2001 products and in early erupted lapilli of the 2002-2003 event and its crystallization constrained at shallow conditions ($P < 200$ MPa and $T < 1000$ °C; Viccaro et al., 2005).

This study aims at investigating the feeding system of rift-related eruptions at Mt. Etna by integrating data from the 2001 and 2002-2003 events with new data collected on samples from 12 historic eruptions from the NE-Rift and from a recently discovered amph-rich cumulitic xenolith, ultimately improving the knowledge of magma ascent and pre-eruptive dynamics in Mt. Etna rift systems. Textural observations of the NE Rift products highlight a greater geochemical and textural variability compared to magmas erupted from the Central Craters, despite a comparable mineral assemblage made of Ol, Cpx, Plg and Ti-Mt. High and low porphyritic lavas coexist in the and are frequently mingled. Whole-rock composition varies from hawaiite-trachybasalt to benmoreite, in contrast with the rather homogenous trachybasaltic composition of magmas erupted from the central craters.

Thermo-barometric estimates based on Ol-Liq and Cpx-Liq equilibria (Putirka et al., 2008) depict a magmatic ascent path with a remarkably lower DT/DP compared to magmas erupted at the central craters. Moreover, the P-T crystallization conditions of amphibole estimated using the thermobarometer of Higgins et al. (2022), provided significantly deeper than previous estimates crystallization P (up to 800 Mpa).

Giacomoni P.P. et al. (2012) - A common feeding system of the NE and S Rifts as revealed by the bilateral 2002/2003 eruptive event at Mt. Etna (Sicily, Italy). Bull. Volcanol., 74, 2415-2433, https://doi.org/10.1007/s00445-012-0672-3.

Higgins O. et al. (2022) - Machine learning thermobarometry and chemometry using amphibole and clinopyroxene: a window into the roots af an arc volcano (Mount Liamuiga, Saint Kitts). Contrib. Mineral. Petrol., 177, #10.

Putirka K. (2008) - Thermometers and barometers for volcanic systems. In: Putirka, K.D., Tepley III, F.J. (Eds.), Minerals, Inclusions and volcanic processes. Rev. Mineral. Geochem., 69, 61-120.

Viccaro M. et al. (2005) - Magma mixing during the 2001 event at Mount Etna (Italy): Effects on the eruptive dynamics. J. Volcanol. Geotherm. Res., 149, 139-159, https://doi.org/10.1016/j.jvolgeores.2005.06.004.

Petrology of Folafótur peninsula basalts (Westfjords, Iceland): chasing the path of the Icelandic hot spot

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Keywords: MORB, feeding system, geopark.

Folafótur Peninsula is a remote 8.3 km long and 1.8 km wide NNE-SSW elongated land stripe sited in the Westfjords (N 65°59'49.47''; W 22°53'40.15''). Despite its distance from the active volcanic zones, it contains some remarkable geologic, geomorphologic and historic features, recently summarized in the paper from Ellero et al. (2023) which ultimately aimed to promote the creation of a UNESCO geopark.

Among the highlighted naturalistic features, the petrology of Miocene-lower Pliocene volcanic products which constitute the peninsula and its more prominently mountain (Mt. Hestur) is still mostly unknown. This study aims to characterize the main petrographic and geochemical features of lava flows and dykes, collected along a stratigraphic sequence around Mt. Hestur.

The studied samples are 10 sub-horizontal lavas and 4 dykes with variable texture ranging from highly porphyritic (P.I. 15-20%) in older lava flow to low porphyritic (P.I. < 5 %) in younger products. All studied samples show a holocrystalline matrix with highly variable crystal size ranging from few tens of μm to 600 μm in most of the lavas and up to 1 mm in the dykes. The phenocrysts assemblage is mainly represented by Pl (70-90%) and Cpx (10-30%), while Pl (60-80%), Cpx (10-30%), Mag (10-20%) and Ol (5-10%) constitute the groundmass. Pl and Cpx often form glomerocrysts, with 80% and 20% relative abundance respectively; opaque crystals are scarce < 5% and mostly included in Pl. The abundance of glomerocrysts decreases in younger lava flows.

Pl phenocrysts are mostly euhedral and characterized by oscillatory zoning and dissolution/regrowth textures at the cores and/or at the proximity of the rims. This feature suggests a highly dynamic feeding system which is worthy of further detail in-situ investigation.

The whole-rock composition has been determined by means of X-ray fluorescence (XRF) at the Department of Physics and Earth Sciences, University of Ferrara. All the samples are sub-alkaline tholeiitic basalts with SiO_2 varying from 48.56 wt% to 50.52 wt% and total alkali from 2.7 wt% to 3.4 wt%. The Mg# varies from 38.5 to 56.4 while TiO_2 varies from 1.58 wt% to 3.13 wt%.

The geochemical and petrographic studies of the samples can be integrated with the stratigraphic sequence, which is characterized by discontinuous layering of volcanic levels, polygenic sedimentary deposits, and some discordant structures (such as dykes). The results show an initial slight increase in SiO_2 content in time from 45.48 wt% to 49.75 wt%, followed by a minor decrease to 49.55 wt%.

Further electron microprobe (EPMA) study of mineral textures and chemical composition as well as trace element analyses by means of inductively coupled mass spectrometry (ICP-MS) will be performed with the aim to investigate pre-eruptive magma processes and eventually discriminating between MORB and OIB-like mantle source.

Ellero A. et al. (2023) - Geology and geodiversity of the Folafótur peninsula (Westfjords, Iceland). J. Maps., 19, 1.

In-situ geochemical and isotopic evidence of a complex magma dynamics at the Marsili Seamount

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Keywords: Marsili Seamount, crystal zoning, isotopic signatures.

Marsili is a 3500 m-high, 60 km-long and 20 km-wide seamount that extends along a NNE-SSW direction in the southern Tyrrhenian Sea, with its summit located ~500 m below the sea-level. The Marsili seamount (MS) poses as a source of volcanic hazard to the entire Tyrrhenian region, especially due to the threat of tsunamis triggered by sector collapses and flank failures driven by gravitational instability or renewed volcanic activity.

The origin of the MS (~0.7 Ma) is associated with back-arc extensional processes resulting from the northwestward subduction of the Ionian Plate below the Calabrian Arc and southeastward rollback of the subducting slab. Throughout its history, the MS has predominantly erupted arc-like lavas. However, few lavas derived from the axial zone of the MS exhibit a more alkaline, intraplate affinity, reflecting the influence of asthenospheric mantle flow into the mantle wedge – potentially enhancing magma supply within the volcano's plumbing system (Trua et al., 2011).

Previous studies of lava samples dredged from different sectors of the MS revealed a compositional range from prevalent basalts to less common andesites with mineral assemblages dominated by olivine, clinopyroxene, plagioclase with minor amphibole and biotite. These studies primarily focused on bulk-rock and mineral characterization, while detailed textural analyses and *in-situ* compositional and isotopic investigations remain lacking.

Here, we present new *in-situ* major and trace element data, along with Pb and Sr isotopic compositions of matrix glasses, plagioclase, and clinopyroxene crystals from a suite of basaltic to andesitic samples from the MS. Trace element and Pb isotopic compositions of matrix glasses indicate that the most evolved magmas did not entirely derive from the least evolved ones through fractional crystallization processes. Plagioclase and clinopyroxene crystals exhibit a variety of zoning patterns that correlate with variations in major and trace elements as well as Sr isotopic ratios, suggesting that magma recharge events involved melts of different origin.

This work provides new insights into the magmatic processes operating within the Marsili plumbing system that are crucial for understanding the volcano's dynamic behavior and assessing its associated volcanic hazards.

Trua T. et al. (2011) - Magmatic evidence for African mantle propagation into the southern Tyrrhenian backarc region. Geol. Soc. Am. Spec. Paper, 478, 307-331.

Tracing the pre- to post-eruptive crystallization of trachybasaltic melts: the 1651-1654 CE lavas of Mount Etna (Sicily, Italy)

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Keywords: magma ascent, lava crystallization, crystal growth rate.

The reconstruction of crystallization dynamics of silicate melts is crucial for understanding the processes taking place from magma rising to the flowing of lavas, the latter posing the major hazard for human infrastructures and settlements during effusive eruptions (Troll et al., 2024). Crystal growth and H_2O degassing have deep impact on the rheological properties of lavas and govern their path on the surface. In this work, the pre- to post- eruptive crystallization of trachybasaltic melts was investigated by studying the lavas emplaced during the 1651-1654 CE eruption on the western flank of Mount Etna volcano (Sicily, Italy). This event stands out as one of the most important of the 17th Century due to its prolonged duration, the extension of the lava field, and its reach into inhabited areas on the volcano flank (Branca & Abate, 2019).

Investigation on different layers of a fractured pressure ridge allowed to reconstruct the crystallization history of a single unit flow, revealing significant textural differences between the core and crust of the lava, allowing to quantify the extent of crystallization at subaerial conditions. A multi-technique approach combining 2D and 3D (Synchrotron Radiation computed microtomography) textural analyses, chemical (X-Ray Fluorescence), spectroscopic (Fourier-Transform InfraRed spectroscopy), and mineralogical (X-Ray Diffraction and Electron Probe Microanalysis) methods allowed to constrain the pre- to post-eruptive conditions of crystallization.

Results indicate that the crystal cargo is dominated by phenocrysts which mostly started nucleating at relatively low T-P conditions ($P < 0.7$ kbar; $T \leq 1070$-1060 °C), while Mg-rich antecrysts are not present. Crystallization continued after emplacement, during the lava flow. In the glass-rich crust, detailed textural and chemical analyses revealed the presence of a chemical boundary layer around plagioclase microlites. Using the model of Lucassen et al. (2009), their subaerial growth rate was estimated to be in the order of 0.2-4.5 μm/s, which bear witness to the fast timescales (minutes) of ultimate cooling of the flow. These results enhance our understanding of lava behaviour during emplacement and pose the basis for future improvement in predictions of mafic lava paths, leading to better monitoring and response during volcanic crises similar to the 1651-1654 CE eruption.

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Troll V.R. et al. (2024) - The 2021 La Palma eruption: social dilemmas resulting from life close to an active volcano. Geology Today, 40(3), 96-111.

From deep to shallow magma storage system in OIB volcanoes: a case study of Santiago and Santo Antão (Cape Verde)

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Keywords: fluid inclusions, OIB magmatism, magma plumbing system.

The Cape Verde archipelago represents a key volcanic setting in Eastern Atlantic for investigating the dynamics of OIB magmatism. Despite its long-lived and spatially distributed volcanic activity, the architecture and evolution of magma plumbing systems beneath the less active islands remain poorly constrained. Understanding the depth, structure, and temporal variability of these systems is crucial for deciphering mantle melting processes, crustal magma storage, and volatile transfer from source to surface. In this context, the role of deep CO_2-rich fluids and their entrapment in fluid inclusions provides valuable insights into the volatile budget and magmatic evolution beneath Cape Verde.

In this study, we present novel microthermometric analyses of pure CO_2 fluid inclusions hosted in olivine and pyroxene phenocrysts from basanitic and foiditic (SiO_2 ~42 wt.%, MgO ~11.2 wt.%, and $K_2O + Na_2O$ ~4.1 wt.%) tephra samples to reconstruct the evolution of trans-crustal magma plumbing systems beneath Santiago and Santo Antão islands in the Cape Verde archipelago. The results reveal, a vertically extensive and complex architecture of the magma plumbing system, comprising: a deep magma reservoir (~31–33 km, Santiago; ~38–40 km, Santo Antão), a main magma storage zone (~23–25 km, Santiago; ~20–30 km, Santo Antão), and a magma stagnation zone near the mantle–crust boundary (~18–20 km, Santiago; ~10–14 km, Santo Antão). Compared to previous barometric estimations from Fogo volcano (Cape Verde), we find that these systems are characterized by multiple magma storage levels populated by small magma batches and separated by non-eruptive crystal mush zones. Our findings will be integrated with ongoing analyses of pre-eruptive volatile contents in melt inclusions to (i) tracking spatio-temporal variations in CO_2 concentrations in the mantle source beneath Cape Verde; (ii) constraining the carbon content of the mantle source; (iii) expand current knowledge on OIB volcanism.

Reactive dissolution of plagioclase in a basaltic melt: a chronometer for pre-eruptive volcanic processes

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Keywords: Stromboli, plagioclase, reactive dissolution.

Dissolution and reaction textures of plagioclase phenocrysts in basaltic rocks testify to perturbations of the magmatic system that are frequently associated with pre-eruptive mixing processes. We present results from dissolution-reaction experiments performed at 150 MPa and 1150-1300 °C, used to examine and quantify the timescales of dissolution of plagioclase in a basaltic melt (Masotta et al., 2025). Simple dissolution occurs under high degrees of plagioclase undersaturation, whereas, at conditions near the plagioclase liquidus, reactive dissolution is expressed by a noticeable decrease in crystal size and the formation of An-rich reaction zones. The total amount of crystal dissolution and the width of the reaction zone increase with time according to an exponential law, yet more rapidly than what predicted by assuming diffusion in plagioclase as the rate limiting factor. The remarkably fast dissolution rate (~10-8 m/s) is explained by the formation of planar dissolution interfaces that initially accelerate the dissolution process, whilst the increasing textural maturation of the reaction zone counteracts this effect. A chronometer for retrieving the timescale (t) of reactive dissolution from the width of reaction bands and rims ($d_reaction$) in plagioclase phenocrysts contained in basaltic rocks is derived from the experimental data:

$$t\ (\text{min}) = [1.408 * d_reaction\ (\mu\text{m})]^{1.178}$$

The application of this chronometer to Stromboli volcano (Italy), where reaction rims in plagioclase are attributed to the pre-eruptive mixing between a deeper volatile-rich magma (lp-magma) with a degassed magma residing at shallow depths (hp-magma), permits to determine a characteristic timescale of 161±43 minutes for mixing episodes preceding more energetic eruptions.

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Crystallization dynamics in magmas recorded by clinopyroxene: a multifaceted perspective

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Keywords: clinopyroxene, magma dynamics, crystallization kinetics.

Clinopyroxene is one of the most abundant mineral constituents of igneous rocks, and both its texture and composition are highly sensitive to variations in magma crystallization histories. Although most clinopyroxene-based thermometric, barometric, and partitioning models assume archetypal equilibrium-controlled solution energetics, magma solidification beneath active volcanoes typically takes place in chemically and physically perturbed plumbing systems. In such environments, the crystallization of clinopyroxene is collectively driven by a range of kinetic processes related to the dynamics of crustal reservoirs and eruptive conduits. Hence variable cooling, decompression, degassing, and convective mass transfer regimes critically influence the textural and compositional evolution of clinopyroxene crystals in the erupted products. Existing petrological models derived from unperturbed clinopyroxene-melt exchange reactions hold unquestionable importance and merit, yet they do not fully capture the complexity of natural subvolcanic environments, for which the phenomenological treatment of reaction kinetics plays a pivotal role in the evolution of energetically unstable magmatic systems. The ultimate goal of this scientific communication is to illustrate how the textural attributes of clinopyroxene, the mixing properties of solid solution components and, the partitioning energetics of major-trace cations between clinopyroxene and melt are axiomatically dominated by the shift from equilibrium to dynamic crystallization regimes. Examining the interplay between kinetics and thermodynamics throughout the composite growth history of clinopyroxene offers a robust framework for a more comprehensive understanding of magmatic processes across multiple interconnected crustal reservoirs and during eruption towards the surface.

The quest for what modulates the oxidation state and its far-reaching consequences on magma evolution

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Keywords: oxidation state, melt reactivity, thermodynamics.

Magma is the most important transport agent throughout our planet and as such it is the main carrier of oxygen through Earth's interiors up to the surface. Magma liquid portion, the silicate melt, operates as a very efficient high-temperature chemical solvent for metal oxides as well as volatile components. The redox state of magmas then refers to the ensemble of conditions and variables governing the oxidation state of metals, volatiles and the species they form, either dissolved in the melt or exsolved in a coexisting fluid. Parameterization of the redox state is fundamental to assess mass and energy transfer in magmas, phase equilibria and then P–T conditions at which these take place. Magma redox state is then representative of the environment in which magma evolves and it is usually reported as oxygen fugacity, a key thermodynamic variable. Involved in polybaric physiochemical interactions, fO_2 is used to fix melt saturation properties and the speciation of fluids. Briefly, knowing oxygen fugacity is central for the understanding of melt-volatiles interactions. Melt-volatile interactions may occur in either closed- or open-system conditions, the latter being representative of 1) volatile outflow (degassing), 2) volatile inflow (regassing), or 3) flow-through processes. In the literature we often refer to "gas-fluxing" when mechanism 2) or 3) occur and leave indirect testimony of their action in crystal-armored melt inclusions, via chemical or textural signatures in mineral assemblages or via mass imbalances emerging by the joint assessment of fluxes and composition of volcanic gas emissions, especially at open-conduit volcanoes.

The modeling of these effects, however, require rigorous thermodynamic approaches about the true nature of melt reactivity, whose oxidation state, hence fO_2, are just a reflection. Nevertheless, several popular oxybarometers, especially based on sulfur and iron species, are used which do not account for the melt reactivity and thus cannot answer the main question: "what controls what ?".

Examples and case studies are here reported, such as:

a) The inevitable fO_2 decrease that occurs during magma ascent (unless "external" factors intervene) despite the relative increase of bulk oxygen in the system *via* differentiation;
b) the main role of dissolved water in shifting the oxidation state together with the possibility of volatile influx (re)melting and so-called redox melting;
c) The model-dependent contrasting results on sulfur equilibria and partitioning, with major implications for the interpretation of time series of volcanic gases.

The examples provided, some of which targeted to Italian volcanic systems, clearly show that the study of the mixing properties of silicate melts is still the most important issue. The redox thermodynamics of melt systems reveals effects too often considered marginal but which – on the contrary – might be dominant in some geodynamic systems.

Titanomagnetite growth kinetics as a proxy for major and trace cation substitution reactions

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Keywords: titanomagnetite, growth kinetics, cation substitutions.

Titanomagnetite is a common phase in mafic alkaline magmas, and its textural and compositional variability often reflects a range of differentiation processes occurring within shallow crustal reservoirs and eruptive conduits of active volcanoes. At temperatures above 600 °C, titanomagnetite forms a complete solid solution between two endmembers: 1) magnetite (Mt; Fe_3O_4), and 2) ulvöspinel (Usp; Fe_2TiO_4). This solid solution can be expressed as $Fe_{3-x}Ti_xO_4$, where 0P = 30–300 MPa, T = 1050–1150 °C, f_{O2} = NNO + 1.9-NNO + 2.3, and melt-H_2O = 0.6–4.4 wt.%. Combined electron microprobe and laser ablation data indicate that titanomagnetite growth kinetics primarily control the Usp component, which in turn exerts a first-order influence on the incorporation of transition metals and high field strength elements into the crystal lattice. It follows that physical and chemical perturbations within highly dynamic plumbing systems may deeply affect the partitioning energetics of cation substitutions, with important repercussions for the geochemical evolution of magmas.

Subvolcanic rocks as recorders of magmatic evolution: U–Pb zircon and titanite geochronology of phonolite dykes and plutonic rocks from the Predazzo complex (Southern Alps, Italy)

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Keywords: phonolites, U-Pb geochronology, Dolomites.

Well-preserved ancient volcano-plutonic complexes offer a rare opportunity to investigate the magmatic record and deepen our understanding of their formation and evolution. The Permo-Triassic magmatic evolution of the Southern Alps (Italy) is intensely studied due to its complex geodynamic context and the remarkable preservation of stratigraphic relationships with adjacent metamorphic and sedimentary units. In the Southalpine domain, major pulses of volcano-plutonic activity are bracketed by the emplacement of smaller-volume magmas of variable geochemical affinity, preserved as dykes and veins intruding plutonic and volcanic sequences. These manifestations enable the reconstruction of magma source evolution and the timing of the magmatic episode. Here, we present the first integrated geochemical and geochronological study of highly evolved alkaline phonolitic dykes, along with a comprehensive geochronological survey of the Predazzo pluton. The sodalite- and aegirine-bearing phonolites, intruding Middle Triassic volcanic sequences, contain titanite, apatite, and magnetite as accessory phases and display trace element patterns consistent with the orogenic-like geochemical signature of the broader Predazzo magmatic system. U–Pb dating on titanite (phonolite dykes) and zircon (plutonic units) reveals dyke emplacement between 233.8±3.1 Ma and 238.1±4.5 Ma, overlapping and slightly postdating the crystallisation of the Predazzo pluton (237.97±0.15 Ma to 238.31±0.13 Ma). The dating reveals also the temporal dissimilarity with the alkaline lamprophyre dykes outcropping in the same area (219.22±0.73 Ma; Casetta et al., 2019) highlighting the different nature of the two occurrences. Mineral-based thermometry and hygrometry indicate that the phonolites represent volatile-rich (H_2O = 8±0.6 wt%), REE-enriched, highly differentiated melts, emplaced at relatively low temperatures (752–868 °C), potentially driving associated Cu–W mineralisation. Comparisons with coeval intrusions in the Edolo (Central Alps) and Finero (Western Alps) complexes confirm that these phonolites preserve the orogenic geochemical signature characteristic of pre-Alpine Tethys magmatism. These new constraints clarify the temporal and petrogenetic framework of the Predazzo volcano-plutonic complex and provide insights into the link between alkaline magmatism and mineralisation processes during the Middle Triassic.

Casetta F. et al. (2019) - The alkaline lamprophyres of the Dolomitic Area (Southern Alps, Italy): markers of the Late Triassic change from orogenic-like to anorogenic magmatism. J. Petrol., 60(6), 1263-1298, https://doi.org/10.1093/petrology/egz031.

Depth of magma reservoir as a key-factor in the genesis of pure Plinian vs. caldera-forming eruptions: experimental constraints

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Keywords: experimental petrology, primari analcime, pure Plinian vs. Caldera-forming events.

Understanding the physico-chemical conditions governing magma plumbing systems is a key focus in volcanological investigations. In particular, the evolution of eruptive processes and the correlated eruptive phenomena are linked also to pressure conditions, whose precise estimation is still subject of debate. In this context, investigating phase relationships and stability fields of mineral phases sensitive to variations in pressure, temperature, and volatile content can provide valuable insights. During a recent geological survey on Ventotene Island (Pontian Islands, Tyrrhenian Sea), primary analcime, which according to the literature is stable at P_{H2O} > 200 MPa, was observed in the Cala di Battaglia unit (UCB), which consists of a sequence of Plinian fall deposits with no evidence of associated pyroclastic currents. Conversely, analcime is absent in both the Plinian fall and pyroclastic flow deposits from the Parata Grande caldera-forming event. To investigate the role of pressure and volatile content (H_2O) on phase equilibria in alkaline differentiated magmas, experimental studies were conducted at pressures of 150 and 600 MPa on two different compositions, MD1 tephri-phonolite from Parata Grande, and UCB2 trachy-phonolite from Cala di Battaglia, in both under-saturated and over-saturated water conditions. For the tephri-phonolite composition MD1, only the 600 MPa pressure condition was preliminarily explored, while experiments on the trachy-phonolite UCB2 were performed at both 150 and 600 MPa. Experimental temperatures ranged from 700 °C to 1050 °C. The main experimental results show that in the H_2O-undersaturated experiments on MD1, the mineral assemblage consists of clinopyroxene+biotite+apatite+oxide at 1050 °C, followed by plagioclase (900 °C) and K-feldspar (840 °C), while in the over-saturated ones (950 °C) the paragenesis is composed of mica, clinopyroxene, plagioclase, oxide and apatite. For what concerns experiments on the UCB2 composition, in the high-pressure set, a hydrous feldspathoid associated with plagioclase and biotite occurs at 900 °C, followed by K-feldspar at lower temperature (750 °C). Conversely, in the low-pressure set products, the hydrous feldspathoid is absent and the mineral assemblage consists of K-feldspar, plagioclase, biotite and oxide. These experimental results suggest that hydrous feldspathoid minerals are unable to crystallize from a H_2O-saturated trachy-phonolitic magma in shallow (≤150 MPa) reservoirs. This evidence supports the hypothesis that the depth of the pre-eruptive magma system is a primary factor controlling pure Plinian (e.g. Cala di Battaglia) vs. caldera forming events (e.g. Parata Grande).

Experimental study of clinopyroxene-melt reaction: implication on crystal-mush reactivation by primitive alkaline melt.

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Keywords: crystal mush, dissolution-reaction experiments, Campi Flegrei.

Zoned phenocrysts are very frequent in lava samples and provide evidence of magma replenishment and subsequent reaction. Several lines of evidence indicate that magmatic reservoirs reside for most of the time in a mush state, frequently perturbed by injection of new magmas that changes the system from a 'lock-up' magma to a crystal-rich suspension able to erupt. Crystal dissolution and/or growth during magma mixing often result in phenocryst populations that display disequilibrium textures, wide compositional variability and zoning. The latter feature is commonly used to calculate crystal residence time or magma ascent rate or the time elapsed between the refilling of a new more mafic magma into sub-volcanic magma chambers and eruptions. However, the dissolution-crystallization process during crystal-melt interactions has received limited attention in previous studies (Bonechi et al., 2022; Perinelli et al., 2023). Therefore, in order to investigate on the chemical consequences of crystal-melt interaction, here we report the results of new reaction experiments conducted on melt-clinopyroxene crystals (cpx) by using as starting materials a Campi Flegrei K-basalt (APR16 sample) and diopsidic clinopyroxenes in chemical disequilibrium with the K-basaltic reacting melt. The experiments were carried out at the HP-HT Laboratory of the Department of Earth Science of Sapienza University of Rome in a piston cylinder apparatus at 600 MPa and 1300 °C, a temperature ~30 °C above the liquidus temperature of APR16 K-basalt at the investigated pressure. Runs duration was variable from 15 to 90 minutes. Preliminary findings show that cpx dissolves in the first 15 minutes of the experiment. The cpx grains display rounded crystal edges and generally sharp clinopyroxene-glass interface. Locally, glass-filled channels and/or small pores are observed entering the clinopyroxenes, as a result of cracks or cleavages. By increasing the experimental dwell time to 30 minutes, the cpx exhibit both dissolution and recrystallization features marked by the overgrowth of a thin (~10-15 μm) rim on the smoothed edges of the pristine clinopyroxene. In these experiments, a dense population of euhedral, small (< 15 μm), short-prismatic zoned clinopyroxenes surrounds the initial cpx. Results of these dissolution reaction experiments suggest that a temperature fluctuation of about 30 °C induces a rather rapid partial re-equilibrium between clinopyroxene and the K-basaltic melt. This indication may have implications for how easily a mid-lower crustal mush zone, such as that revealed beneath the Campi Flegrei (Isaia et al., 2025) and consisting of clinopyroxene-rich cumulate (Perinelli et al., 2019), can be unlocked by the injection of batches of new primitive upper mantle magma.

Bonechi B. et al. (2021) - High pressure experimental investigation of clinopyroxene dissolution in a K-basaltic melt. Chem, Geol., 584, 120533, https://doi.org/10.1016/j.chemgeo.2021.120533.

Isaia R. et al. (2025) - 3D magnetotelluric imaging of a transcrustal magma system beneath the Campi Flegrei caldera, southern Italy. Commun. Earth Environ., 6, 213, https://doi.org/10.1038/s43247-025-02185-5.

Perinelli C. et al. (2019) - Effect of water on the phase relations of primitive K-basalts: implications for high-pressure differentiation in the Phlegraean Volcanic District magmatic system. Lithos, 342-343, 530-541, https://doi.org/10.1016/j.lithos.2019.05.032.

Perinelli C. et al. (2023) - Experimental cannibalization of plagioclase by alkaline basalt magmas. Per. Mineral., 92, 75-95, https://doi.org/10.13133/2239-1002/17931.

Multi-elemental assessment of plagioclase-melt equilibria unravels episodes of crystal growth and provides clues on magma evolution

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Keywords: thermobarometry, crystal-melt equilibria, plagioclase.

Violent eruptive events in basaltic systems often follow input of hot, undegassed magmas in shallow magmatic reservoirs. Investigating how crystal and glass chemistry record such physicochemical changes in the system is critical to reconstruct the mechanisms driving sudden large scale explosive events in such settings, and may be integrated with crystal stratigraphy to recover the relative and absolute timing of eruption triggers. As such, it is of utmost importance to reconstruct such changes in natural systems through the record provided by crystals and glasses in the eruption products.

The reconstruction of crystal-melt equilibria is crucial for a thermodynamically rigorous assessment of intensive properties of the magmatic system based on mineral compositions. In this respect, experimental constraints on crystal-melt partitioning are quintessential to the modeling of melt compositions and intensive parameters, performed by minimizing the strain energy determined by the substitution of isovalent trace cations in crystal lattice sites. In this contribution we combine numerical modeling with a multi-elemental approach, calibrating new parametrizations for elemental partitioning and physicochemical conditions of the magmatic system. We applied this model to the study of intracrystalline compositional variations in a statistically representative data set of plagioclase compositions from Stromboli volcano. This approach, applied to a well-studied volcanic system, allows to constrain the chemical evolution of the system, assessing the role of disequilibrium effects and transient melt compositions existing ephemerally during crystal growth and dissolution episodes. Implications of this work extend from the establishment of a novel approach to crystal-melt equilibria, to the definition of best practices to deal with the interdependence inherent in the treatment of intensive thermodynamic properties of magmatic systems, to the reconstruction of magma dynamics in active and hazardous volcanic systems.

Integrating Sentinel-2B and GIS tools for volcanic lava flow age mapping: a multisite validation study

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Keywords: satellite imagery, multispectral analysis, GIS-based toolbox.

Lava flow dating is a fundamental aspect of volcanology, contributing to the understanding of eruption histories, hazard assessment, and volcanic evolution. Traditional dating methods, such as radiometric techniques, provide high precision but are often costly, time-consuming, and limited to accessible sites. Recent advances in satellite remote sensing offer a powerful alternative for estimating lava flow ages over extensive and often inaccessible volcanic terrains. Multispectral and hyperspectral imaging enables the detection of mineralogical and chemical changes that occur as lava flows undergo weathering and oxidation over time. Among the most relevant indicators of lava flow aging is the oxidation state of iron, which transitions from ferrous (Fe^{2+}) to ferric (Fe^{3+}) forms as a function of exposure to atmospheric and environmental conditions. The Sentinel-2B satellite, part of the Copernicus program, provides high-resolution multispectral data suitable for capturing these spectral variations. This study presents a novel methodology for estimating the relative ages of lava flows by leveraging Sentinel-2B imagery and GIS-based processing. The approach involves the development of a custom toolbox within ArcGIS Pro, named "Polygrid," designed to preprocess satellite images by removing vegetation and moisture effects. Additionally, spectral band ratios are utilized to highlight Fe^{2+} and Fe^{3+} distributions, facilitating the construction of a Fe^{3+}/Fe^{2+} ratio image for age estimation. The results are validated against known eruption dates to assess the accuracy and reliability of the proposed method. This study focuses on four volcanic regions characterized by diverse geological settings and well-documented eruption histories: Mount Etna (Italy), Stromboli (Italy), Kīlauea (Hawaii), and the Grindavík region (Iceland). These locations were selected due to their frequent lava flow activity and availability of independent age constraints for validation.

Phenocryst textures, chemistry, and in situ Sr isotopes of The Pleiades Volcanic Field (Antarctica): a plumbing system modulated by ice load fluctuations

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Keywords: volcano plumbing system, Antarctica, volcano-ice.

The Pleiades Volcanic Field (PVF), in northern Victoria Land, Antarctica, comprises a dozen monogenetic scoria cones and two domes, with ages ranging from ca. 800 ka to the present. Despite the monogenetic aspect of the edifices, the volcanic products display high petrological and geochemical variability, following two distinct evolutionary paths: (i) a complete, mildly Na-alkaline differentiation trend from alkali basalt to trachyte; and (ii) a strongly alkaline, less complete trend, with compositions ranging from tephrite to phonolite. These characteristics make the PVF a distinctive volcanic field, whose plumbing system likely experienced an evolution more complex than expected for typical monogenetic volcanoes.

To unravel the architecture of the PVF plumbing system, we characterised the chemistry, texture, and P-T conditions of crystallisation of the crystal cargo from a set of lavas representative of the entire association. In addition, we performed in-situ Sr isotope determinations on feldspars and groundmass using laser ablation multi-collector mass spectrometry (LA-MC-ICP-MS).

The crystal cargo exhibits a wide variety of textures (dusty mantles, coarse sieve textures, rounded cores), along with zonings in major (e.g., Ca-Na, Mg-Fe) and trace elements (e.g., Ba, Cr, Ni), as well as Sr isotopic ratios (ranging from 0.7036 to 0.7043). Machine-learning-based thermobarometric estimates indicate that crystallisation occurred over a pressure range between 1.2 and 0.1 GPa, with a significant cluster at around 0.3 GPa. Our results imply effective exchange and recycling of crystals between differently evolved magma batches, characterised by distinct radiogenic isotope signatures. The refilling by low $^{87}Sr/^{86}Sr$ basaltic magma of a highly radiogenic magma in a shallow reservoir before eruption is evidenced in the most mafic terms of the association.

We thus infer a long-lived and vertically extending subvolcanic system, periodically feeding the volcanic activity for hundreds of thousands of years. The complex evolution of the plumbing system of the PVF, in a volcanic province where numerous monogenetic cones are primarily mafic in composition, can reasonably have been forced by external factors. In the context of glaciated terrain, and considering that the PVF is located inland with respect to most of the other McMurdo volcanic rocks in northern Victoria Land, a plausible efficient forcing is the variation of the ice load, linked to climatic fluctuations, which can influence the stress field conditions around crustal magmatic reservoirs.

Petrological exploration of magma storage and evolution conditions at the eastern Virunga Volcanic Province (Rwanda, East African Rift System)

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Keywords: Virunga Volcanic Province, alkaline volcanism, plumbing system.

The Virunga Volcanic Province (VVP) in the western branch of the East African Rift System hosts a variety of alkaline lavas erupted from closely spaced volcanic centers. Yet, knowledge of the magmatic system that lies beneath this region is still limited, particularly in its eastern sector.

To contribute to understanding this issue, we conducted a petrological investigation on a suite of five lava samples from the eastern sector of the VVP. The investigated samples are random blocks collected near the village of Ruhengeri, which is very close to the Sabinyo, Gahinga, and Muhavura volcanoes. The samples suite comprises two basalts, one trachyandesite, and two trachyandesites.

A notable match is observed between the bulk-rock geochemical features of these five lava samples and those previously recognized in lavas from the Gahinga and Muhavura. In Harker diagrams of major and trace elements, these samples define compositional trends that closely correspond to the basalt-to-trachyandesite compositional trend obtained when considering the few geochemical analyses available for the Gahinga and Muhavura lavas. A similarity is also observed between the chemistry of the mineral phases (i.e., olivine, clinopyroxene, and plagioclase) hosted in the analyzed samples and the basalts from Muhavura volcano. Overall, these similarities suggest that the whole-rock and mineral analyses of this study can provide quantitative insights into aspects related to the magmatism of the eastern VVP region.

Thermobarometry on the minerals present in the investigated lava samples indicates an origin from magma storage zones distributed between 4–30 km depth. Temperatures and H_2O melt contents vary from 1200 to 1050 °C and from < 1 wt% to 2–4 wt% in the basaltic and the more evolved magma storage zones, respectively. We use the energy-constrained thermodynamic model Magma Chamber Simulator to test whether the major element variation trends exhibited by the studied lava samples conform to a magmatic evolution scenario controlled by fractional crystallization of the mineral phases found as phenocrysts in these samples. The results of the thermodynamic modeling indicate that extensive (up to 70%) crystallization of a mineral assemblage made mainly of olivine, clinopyroxene, and plagioclase can produce the more evolved trachytic derivatives from parental basaltic melts.

Based on the results of this study and those of previous petrological investigations referred to the other VVP volcanoes, a well-developed multi-level plumbing system appears to lie beneath the VVP region. Further detailed petrological studies on lava suites from the VVP region are necessary to offer a more complete model for such a complex plumbing system.

The journey of basalt in vacuum

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Keywords: terrestrial planets, magma, crystallisation kinetics.

Basaltic magmas, ubiquitous on terrestrial planets and moons, undergo crystallization processes that are highly sensitive to variations in pressure, cooling rate and oxygen fugacity. To simulate the physicochemical conditions of planetary surface lavas, particularly those on airless bodies such as the Moon and Mercury, we used a novel high-temperature vacuum apparatus — *Furnace Vacuum Space Melts* (*FV-Smelt*) — specifically designed to perform crystallization experiments on silicate melts at temperatures up to 1500 °C and pressures as low as 10^{-5} bar. This study focuses on the crystallization behaviour of a natural basaltic glass subjected to controlled cooling rates of 1000, 100, and 10 °C/h over a temperature window of 1400–800 °C at a pressure of 10^{-5} bar. Experiments were conducted in graphite crucibles to replicate, as much as possible, reducing conditions analogous to those found in extraterrestrial volcanic environments. The low-pressure regime and the applied undercooling, facilitates the formation of non-equilibrium textures. In situ observation and subsequent petrographic and SEM-EPMA analyses reveal the crystallization sequence, phase assemblages, and textural development. The *FV-Smelt* system enables precise spatiotemporal tracking of nucleation and crystal growth dynamics, allowing direct assessment of chemical evolution during crystallization. These experimental conditions also bear relevance for understanding early solar system processes such as chondrule formation, where rapid cooling and low ambient pressures are key factors. Preliminary results suggest that the observed textures and mineral chemistries approximate those seen in natural planetary basalts, validating the *FV-Smelt* device as a powerful tool for planetary studies.

S7.

Earthquake faulting as a short-term manifestation of the dynamic Earth

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Field and microstructural characterization of Valsesia pseudotachylytes (Ivrea Zone, Italy)

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Keywords: pseudotachylytes, earthquakes, Ivrea Zone.

Pseudotachylytes are solidified frictional melts produced in silicatic rocks during earthquakes (Sibson, 1975). They form as fault and injection veins, with thickness ranging from some millimetres to some centimetres. Still, exposures of meter-thick pseudotachylytes associated to seismic faulting have been documented (Musgrave Ranges, Australia; Lofoten Island, Norway; Ivrea Zone, Italy). While thin pseudotachylytes in the Ivrea Zone have been already extensively investigated, in-depth studies of the giant pseudotachylytes are still lacking. We perform field and microstructural investigations, and preliminary numerical modelling of thin (mm-cm) and giant (up to 1 m thick) pseudotachylytes of the outcrops along the Sesia River (Ivrea Zone, Western Italian Alps) to possibly determine the ambient T-P conditions, the geodynamic setting, and the seismogenic environment of the giant pseudotachylytes, and, in the future, their mechanisms of formation. Three outcrops have been selected (I, II, III) within ~9 km to the E from the Canavese Line (CL, strike ~NNE-SSW), a segment of the Insubric Line (Techmer, 1992; Ueda et al., 2008; Ferrand et al., 2018). No pseudotachylytes have been found to the W of the CL. The main results are:

Outcrop I (< 200 m E from the CL, altered gabbro):

- multiple generations of thin pseudotachylyte-bearing faults and giant pseudotachylyte breccias overprinting microgabbro schlierens. Both are sub-parallel to the CL and the breccias include clasts of the altered (greenschist facies) host rock;
- matrix of the pseudotachylyte overprinted by greenschist facies minerals;
- late quartz- and epidote, and chlorite-bearing faults/fractures cutting the pseudotachylytes.
- Outcrop II (~2 km E from the CL, Balmuccia peridotite):
- multiple giant pseudotachylyte-bearing faults, sub-parallel to the CL, associated with thin pseudotachylyte faults and veins;
- giant pseudotachylytes with homogeneous matrix, suggesting a single friction melt pulse. The matrix (altered into serpentine, talc) includes microlites of olivine and pyroxene plus vesicles;
- serpentine-bearing faults/fractures cutting and cut by the pseudotachylytes.
- Outcrop III (~9 km E from the CL, unaltered diorite):
- only thin pseudotachylyte overprinting/associated with foliated cataclasites cutting and overprinting aplitic dykes, with different strike with respect to the CL;
- pristine pseudotachylyte matrix, with well-preserved microlites, chilled margins and flow structures.

The giant-pseudotachylyte-bearing faults thus are (i) made of a homogenous layer of pseudotachylyte, (ii) sub-parallel and found only near (< 2 km to the E) the CL, (iii) cut and are cut by (sub-) greenschist facies cataclasite-bearing faults, and, (iv) are cut by epidote- and chlorite-bearing fractures and veins. The giant pseudotachylytes could be generated by large in magnitude earthquakes, associated with the activity of the CL and thus of Alpine age.

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Experimental investigation of the role of weak graphite patches in fault stability

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Keywords: fault stability, weak patches, acoustic emission monitoring.

The stability of faults in the shallow brittle crust is strongly influenced by discrete zones of reduced friction, which in natural settings can be represented by graphite-rich patches along fault surfaces (Ooashi et al., 2013). In this study, we present a laboratory framework for exploring how graphite weak patches govern fault slip behaviour and stick–slip nucleation under slow loading conditions (Rutter et al., 2013). Using the newly developed "BeeAx" biaxial apparatus, we prepare 15 × 17 cm rock slabs whose sliding surfaces are modified with graphite patches of controlled size and spatial distribution, embedded within otherwise intact rock. The apparatus's dual servocontrolled rams impose independently regulated horizontal and vertical stresses up to 450 kN, while high-resolution monitoring is achieved through pressure transducers, displacement transducers, and an array of 16 acoustic-emission (AE) sensors.

We explore a range of tectonically relevant sliding velocities, from slow to very slow from 5 µm/s down to 0.05 µm/s, to capture the transition from stable creep to stick–slip failure (Verbene et al., 2020). These low velocities approximate natural nucleation rates in the shallow crust and ensure high temporal resolution of preparatory slip leading up to failure. Real-time AE location algorithms map microseismicity across the fault surface, revealing the spatial relationship between graphite patches and rupture initiation sites. Preliminary observations show that graphite patches reduce the overall peak frictional strength and localize AE activity, while unpatched regions provide mechanical barriers that influence rupture propagation.

This experimental framework will yield fundamental insights into how discrete weak zones affect earthquake initiation and will inform models of induced seismicity and seismic hazard assessment in heterogeneous fault systems (Hirono et al., 2019).

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Verberne B.A. et al. (2020) - The physics of fault friction: Insights from experiments on simulated gouges at low shearing velocities. Solid Earth, 11, 2075-2095, https://doi.org/10.5194/se-11-2075-2020.

3D fault structure controls surface co-seismic slip patterns of the MW7.8 2023 Kahramanmaraş (Turkey) strike-slip earthquake

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Keywords: surface rupture, co-seismic slip, Kahramanmaraş earthquake.

Surface ruptures arising from the reactivation of pre-existing strike-slip faults during individual earthquakes are thought to evolve from an initial stage in which they form highly segmented shear zones through to one in which slip localizes onto a single, throughgoing slip surface, near the surface trace of the pre-existing, underlying fault. However, little is known on how slip is partitioned among adjacent segments prior to localization, and how this varies with progressive slip. To gain insights into this, we here examine a ca. 160 m long, highly segmented strand of the surface rupture of the East Anatolian strike-slip fault that formed during the MW7.8 February 6, 2023 Kahramanmaraş earthquake near the city of Türkoğlu (Turkey). The surface rupture accommodates left-lateral slip of approximately 3.5 m and is comprised of 10 primary segments bounding 9 major stepovers; it intersects at high angle meter-spaced, sub-parallel rows in a ploughed field, enabling detailed slip measurements. We found that slip gradients were initially accommodated through transpression causing vertical displacement (i.e., uplift) within stepover regions. With increasing strain, however, deformation became asymmetrical with the fault segments closer to the surface trace of the pre-existing underlying fault consistently experiencing greater slip. This asymmetry was facilitated by increased synthetic (anticlockwise) layer rotation within stepover regions near the tip of the segments with larger slip. With further slip increments, slip accumulated exclusively on these segments which ultimately formed the throughgoing fault. We interpret this slip asymmetry as indicative of an early tendency of the fault slip localization controlled by the overall 3D structure of the fault.

Seismic and sub-seismic experimental Mirror-like Surfaces in bituminous dolostones

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Keywords: mirror-like surfaces, microstructures, seismic cycle.

Mirror-like Surfaces (MSs) are ultra-polished fault surfaces widespread in carbonate-built, exhumed seismogenic fault zones. Field and experimental investigations indicate that MSs form under a variety of pressure-temperature conditions and slip rates, ranging from "seismic" (≈1 m/s) to "sub-seismic" (≈0.1-100 μm/s) and corresponding to different phases of the seismic cycle. Motivated by the abundance of MSs cutting through bituminous dolostones in the Central Apennines (Italy), we deformed bituminous dolostones gouges using a rotary-shear apparatus at seismic (1 m/s) and sub-seismic (10 and 100 μm/s) slip rates under 20 MPa of normal stress for 1 m of slip displacement. Experiments were conducted under both water-dampened and room-humidity conditions. The experimentally-produced fault surfaces were then analysed using a FEG-FIB-SEM. The main goals were (1) to determine under which loading and ambient conditions MSs form and (2) whether the micro- and nano-structures reveal if the MS formed under "sub-seismic" or "seismic" conditions.

Well-developed MSs (i.e., they reflect light) were produced under both "seismic" and "sub-seismic" deformation conditions, regardless of the presence of liquid water. Similar to natural samples, under the FEG-SEM, all the experimental MSs consist of a film (10s nm thick) made of rounded nanoparticles with well-defined sizes (5-15 nm) lying on top of a 10-100 mm-thick cataclastic slip zone. Lineation on the MSs is due to mechanical grooves recognizable down to the sub-micrometre scale. However, subtle differences are found in the MSs produced at room-humidity conditions: (1) in the "seismic" MSs produced at 1 m/s, the surface is cut by hundreds of nm - few mm long cracks due to thermal contraction or desiccation, and the nanoparticles are arranged in flat, sub-rounded clusters measuring 15-150 nm in diameter; (2) in the "sub-seismic" MSs produced at 100 μm/s and 10 μm/s, the nanoparticles are arranged in sub-spherical clusters measuring only few tens of nanometres. FIB cuts perpendicular to the slip surface reveal that in the "sub-seismic" MS produced at 100 mm/s, the first 2-3 mm of cataclasite beneath the MS is compact and free of porosity while in the "seismic" sample, deformation is more localized and the cataclasite is porous (pores measuring 10s to 100s nm in size). These different sub-micrometre-scale features may affect surface roughness and permeability properties.

Given the variety of deformation conditions (strain rates, temperature, presence of fluids, etc.) that lead to the formation of MSs, they result from the morphological convergence down to the sub-micrometre scale of different physical and chemical processes (e.g., grain boundary diffusion and grain growth, diffusive mass transfer). However, few micro- to nano-structural differences related to the spatial arrangement of the nanoparticles and pores, if preserved in nature, may serve as an indicator of the "seismic" vs. "sub-seismic" origin of MSs.

The role of gravity in normal and reverse faulting earthquakes

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Keywords: dip-slip earthquakes, elastic rebound, strain localization.

The goal of this work is discussing the role of gravity in faulting and earthquake mechanics for different tectonic settings relying on theoretical models, geological observations, and laboratory experiments. The role of gravity in earthquake mechanics has been widely discussed in the literature, and it has been recently used to support the graviquake conceptual model for normal faulting earthquakes (Doglioni, 2024). This model is based on a series of assumptions and conceptual argumentations to explain a distinction between normal faulting and thrust faulting earthquakes.

The role of gravity in different tectonic settings is considered in the Anderson theory of faulting for an elastic medium with brittle rheology. Assuming that the vertical stress is equal to the lithostatic load, and the horizontal stresses are obtained from the sum of lithostatic load and a deviatoric stress, we can compute the principal tectonic stresses changing the sign of deviatoric stress: positive for compressional settings and negative for extensional settings. This simple Andersonian model can explain the differences between normal and thrust faulting earthquakes in terms of different stress state.

The elastic rebound theory is discussed to interpret interseismic strain energy accumulation and localization as well as energy dissipation emphasizing that dynamic processes associated with earthquake ruptures are dissipative and irreversible. The scaling of dissipated energy density with seismic moment does not show any dependence on tectonic setting, corroborating the evidence that coseismic energy release is associated to fracture and frictional processes within fault zones (Cocco et al., 2023). Long-range interseismic strain rate is interpreted in terms of a localized balance between remote tectonic load, gradient of gravitational potential energy and other resisting forces internal to the volume.

Geodetic observations for normal faulting earthquakes can be modeled with conventional dislocation theory without invoking a volume collapse at depth (Segall & Heimisson, 2019) and implying horizontal tensional stresses (negative s3). Normal faulting ruptures release gravitational potential energy, whereas earthquakes on reverse faults expend work in uplifting crustal rocks, but the source of energy driving coseismic ruptures is the same on reverse and normal faults. This does not represent a deviation from the classic theory of faulting and, more importantly, it does not justify the proposition of a different energy balance (gravitational versus elastic) for normal and thrust faulting earthquakes.

Faults are active geological subjects contributing to the strain rate pattern and characterizing the strain localization during the seismic cycle. Considering crustal faults as passive subjects accommodating slip caused by volume collapse is misleading and contradicts geological observations of fault zone structure, laboratory experiments and the spectrum of fault slip behavior.

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Segall P. & Heimisson E.R (2019) - On the integrated surface uplift for dip-slip faults. Bulletin of the Seismological Society of America, 109(6), 2738-2740, https://doi.org/10.1785/0120190220.

From rupture process to earthquake early warning: ideas, methods & preliminary results of the *FORESEEING* project

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Keywords: earthquake source, earthquake dynamics, earthquake early warning.

When an earthquake happens, seismic waves develop at depth and propagate across Earth. In seconds, waves reach the surface, producing devastating effects on population, buildings and infrastructures. Earthquake Early Warning Systems use source information inferred from the real-time recorded signals to alert distant sites before the arrival of the strongest ground shaking. Rapid characterization of the earthquake source process is crucial for the prompt activation of emergency procedures. However, the mechanism of nucleation, radiation and arrest of seismic fractures is still poorly understood and with that, the fundamental issue of seismology is still unsolved: "How do earthquakes begin and what does control their final size?"

The *FORESEEING* project explores the complex physical processes governing the nucleation and early evolution of earthquakes, with the ultimate goal of enhancing Earthquake Early Warning capabilities. To address this challenge, *FORESEEING* adopts a multidisciplinary approach combining observational seismology, laboratory experiments, and numerical modelling. We investigate the signatures of rupture nucleation in real earthquake records to identify potential predictive features in the earliest moments of seismic signals. In parallel, laboratory experiments on rock analogues under controlled stress conditions help reveal the physical parameters that influence rupture initiation and propagation. These insights are further integrated into numerical simulations, to explore rupture dynamics under realistic fault and crustal conditions.

In this contribution, we present the key concepts underpinning the project, describe the methodological framework, and share preliminary results from both observational and experimental work. Early findings suggest that specific characteristics in the initial P-wave signal may carry information about rupture evolution, opening promising perspectives for their incorporation into real-time Earthquake Early Warning algorithms.

Experimental insights into the role of fluid pressure in reactivation of faults with different consolidation states

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Keywords: earthquakes, faults, CCS.

Fluid injection operations, such as CO_2 or hydrogen storage, rely on the presence of permeable reservoir units that may be laterally bounded by fault seals. Characterizing the mechanical and hydraulic properties of these faults, and understanding how they may reactivate during injection, is critical to assessing the long-term integrity and sealing capacity of storage systems. Moreover, fault-bounded reservoirs have historically been exploited for oil and gas production, resulting in a decrease in fluid pressure both within the reservoir and along its bounding faults. This reduction in fluid pressure increases the effective stress acting on the fault zones, leading to over consolidation of the fault rocks.

In this study, we present a series of rock deformation experiments conducted on fault gouges composed of a mixture of calcite, quartz, and clays. The aim is to characterize the mechanical and hydraulic behavior of faults under controlled stress conditions (effective normal stress σ_n'= 20 MPa, $\sigma_n' = \sigma_n - P_f$, where σ_n= normal stress; Pf= fluid pressure) as well as their response to stress changes over time and during fluid injection.

Following the characterization of fault gouge frictional strength and permeability, a series of creep tests were performed. This experimental setup allowed us to investigate fault creep approaching the failure envelope defined by $\tau = \mu * \sigma_n'$, where μ represents the steady-state friction coefficient, τ the shear stress and σ_n' the effective normal stress. We also evaluated the role of pre-existing structural fabrics formed under higher stress conditions than those present at reactivation in governing the behavior of over consolidated faults. In particular, after an initial run-in phase during which the fault gouges developed a fabric and reached a steady-state shear stress, we reduced the shear stress at 40%, 60%, or 80% of the steady-state value, shifting the fault stress state in the (σ_n', τ) space below the failure envelope. This allows fluid injection simulating CO_2 storage activities. Lower shear stress levels (e.g. 40%) facilitated greater fluid injection before reactivation which also means lower effective normal stress, σ_n, promoting enhanced over consolidation.

Key questions addressed include whether deformation remains localized, how strain accumulates over time, and whether gouges exhibit a sort of mechanical memory upon reloading due to over consolidation effects (Giorgetti & Violay, 2021; Pozzi et al., 2022). Additionally, we investigated how fault creep evolves - either remaining stable or transitioning toward accelerated creep or unstable slip depending on the mineralogy and the stress state.

Our results highlight the value of laboratory investigations on fault reactivation under varying stress states. These insights help improve hazard assessment in CO_2 storage operations by enhancing our understanding of injection-induced seismicity and constraining the potential for reactivation of fault-bounded reservoirs.

Giorgetti C. & Violay M. (2021) - The influence of loading path on fault reactivation: a laboratory perspective. Geophysical Research Letters, 48(8), e2020GL091466.

Pozzi G. et al. (2022) - The role of fault rock fabric in the dynamics of laboratory faults. Journal of Geophysical Research: Solid Earth, 127(6), e2021JB023779.

Different paths, same results? Mechanisms for fault mirror development at near surface conditions

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Keywords: fault mirror, earthquake rupture, microstructures.

The investigation of the microstructures that are preserved along exhumed faults is a fundamental window into improving our knowledge of the mechanisms that have been active during a fault's deformation history. The ability to discern the conditions for the development of tectonic fabrics and link them to specific fault slip behaviours (i.e., seismic vs aseismic) and boundary conditions is key to improve our understanding of the mechanisms underlying the seismic cycle at different crustal depths.

We document the occurrence of fault mirrors that formed within a Late Pleistocene to Holocene unconsolidated colluvium fan sitting at the hanging wall of the active Vado di Corno Fault Zone (VCFZ) in the Central Apennines, Italy. Field observations suggest a maximum deformation depth of the faults of c. 50 m and displacement accommodated along single fault surfaces on the order of few mm to cm.

Detailed microstructural analysis of the fault mirrors by means of Focused Ion Beam-SEM, Transmission Kikuchi Diffraction (TKD) and TEM analysis shows extreme strain localization in an up to 10 µm-thick slip zone. The uppermost part of the slip zone is made of euhedral and strain free calcite nanogranular calcite grains (< 500 nm) with pore-filling amorphous material. Locally, the slip zone transitions to a recrystallized layer with calcite crystals being 1-5 µm in size and showing 120° dihedral angles and pitted surfaces at the top. At 2-5 µm away from the fault mirror surface, the grain size increases significantly (up to 10 µm) and calcite grains are often twinned and development of subgrains is frequent.

Our observations strongly resemble microstructures that have been previously documented from carbonate faults exhumed from > 5 km depth and linked to seismic faulting. This consideration raises the question whether the same hypothesized (seismic) mechanisms behind fault mirror formation can be active as well at near-surface conditions as well (without the associated boundary conditions), or if other low-temperature/low-pressure mechanisms may be at play creating the same microstructures. Collectively, our observations provide new documentation into fault mechanics in the uppermost part of the crust.

Formation of fault damage zones in carbonates and their role in the seismic cycle

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Keywords: faults, earthquakes, numerical modelling.

Probably the most impressive geological feature of active fault zones hosted in carbonate rocks is the presence of several hundreds of meter thick damage zones, often made of in-situ shattered rocks (ISRs or rocks made of fragments < 1 cm in size). Despite their abundance, it remains unknown how ISR form (during the propagation of seismic ruptures?), and how their presence affects (1) the propagation of individual mainshock seismic ruptures, (2) the near field wave radiation and associated strong ground motions, and (3) the evolution in space and time of aftershock seismic sequences. In this contribution we will present preliminary results of a 3-years long Ph.D. project aimed at addressing these three main topics with a field geology and numerical modelling approach.

We will exploit available and to be collected field geology data on fault damage zone distributions in the Italian Central Apennines, and will perform dynamic rupture earthquake and seismic sequence modelling simulations with SeisSol (https://seissol.org). The fully-dynamic individual earthquake simulations as well as the seismic cycle simulations with SeisSol rely on the discontinuous Galerkin method, which allows treating complex 3D geological structures, nonlinear rheologies (including off-fault plastic yielding) and high-order accurate propagation of seismic waves (Käser et al., 2010). The earthquake modelling simulations exploit numerical models which integrate frictional constitutive laws obtained from the laboratory with simplified and realistic fault zone geometries. Currently, our study is focused on the Vado di Corno fault (part of the greater Campo Imperatore fault system in the Gran Sasso Massif area) where the damage zones are pronounced and well mapped (Demurtas et al., 2016; Fondriest et al., 2020).

We aim at using the dynamic rupture earthquake modelling simulations as well as seismic sequence modelling simulations to discuss the formation and distribution of ISRs with respect to (1) the maximum magnitude of the earthquake associated to the studied fault, (2) fault geometry (length, presence of step overs, fault bends, etc.), and (3) lithology of the wall rocks. This approach should result in the identification of the physical, geological and loading conditions, which control the propagation of seismic ruptures and the formation and distribution of fault damage zones. The physically based 3D fully dynamic simulations will yield also estimates of earthquake source parameters (e.g., fracture energy, seismic moment release rate) and synthetic seismograms (strong ground motions) to be compared with seismological and strong motions data from earthquakes in the Central Apennines.

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Fondriest M. et al. (2020) - Structural Complexity and Mechanics of a Shallow Crustal Seismogenic Source (Vado di Corno Fault Zone, Italy). Journal of Geophysical Research: Solid Earth, 125(9), e2019JB018926, https://doi.org/10.1029/2019JB018926.

Käser M. et al. (2010) - SeisSol - A Software for Seismic Wave Propagation Simulations. In High Performance Computing in Science and Engineering, Garching/Munich 281-292, https://doi.org/10.1007/978-3-642-13872-0_24.

Fluid-assisted long-term recovery of fractured carbonates: insights from a new experimental apparatus

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Keywords: fluid percolation, fracture healing/sealing, mechanical recovery.

Seismological observations show that earthquakes produce significant changes in the elastic and transport properties of active faults, with co-seismic drops in seismic wave velocities consistently followed by a slow post-seismic recovery, over months to few years. Such variations occur in volumes up to several hundred metres thick that correlate well with the dimensions of fault damage zones. This suggests the existence of a damage-recovery cycle within active fault zones, with the recovery phase possibly driven by a range of fluid-assisted re-strengthening "healing" mechanisms in the fractured medium and/or stress relaxation. Understanding how and how rapidly fractured rocks seal, regain their stiffness, and drive fluid flow in fault zones is fundamental to comprehend the mechanics of the brittle crust and for geo-engineering applications such as geothermal energy, ore deposits, the deep disposal of radioactive waste and CO_2 sequestration.

At the Department of Geosciences of the University of Padua, a "percolation cell" apparatus has recently been installed to study long-term fluid-rock interaction under hydrostatic conditions with a maximum confining and pore pressure of 100 MPa and a maximum temperature of 250 °C. Such apparatus is equipped with two syringe pumps and a back-pressure regulator that allow to monitor permeability evolution through time and a set of high-temperature P- and S- piezoelectric transducers to track changes of rock elastic properties in-situ. In addition, the pore fluid inlet circuit can flow into a stirred autoclave to pump solutions with controlled chemistry up to 20 MPa pore pressure and 200 °C temperature through an externally heated pipe. Such an experimental apparatus allows to study both diffusion- and advection-dominated regimes within conditions representative for the upper crust.

Together with the experimental setup, here we present some long-term percolation tests in which de-ionized water was flowed at 25 °C through rock cylinders of micritic and bioclastic limestones with mated and non-mated single fractures under 20 MPa confining pressure and 5 MPa pore pressure. The temporal evolution of permeability and elastic properties were monitored together with the fluid-chemistry at the outlet. Mechano-chemical processes along the fractures were also investigated through X-ray microtomography and SEM analyses. Our preliminary results suggest a progressive healing of mated-fractures in micritic limestones possibly due to mass-transfer diffusive processes active at local scale.

In addition, long-term percolation of H_2O-$CaCO_3$-CO_2 solution (advective regime) in fractured bioclastic limestones is currently ongoing with the aim to investigate the nature and timing of fracture sealing via mineral precipitation due to temperature increase.

Rock and fluid composition control fault frictional healing in the continental crust under hydrothermal conditions

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Keywords: fluid-rock interaction, fault frictional healing, fluid chemistry.

The process of fault frictional healing, which refers to a fault's capacity to restore its strength over time between seismic events, is a critical factor influencing the seismic cycle (Dieterich, 1972). After a fault experiences rupture during an earthquake, this frictional healing enables the surrounding rocks to accumulate elastic energy, which will be released in the following earthquake.

It is commonly understood that fault frictional healing (or static friction) increases over time and is affected by the fault's rock type or mineralogy. However, most existing studies on frictional healing have been carried out under conditions that do not accurately mirror the environment encountered at seismogenic depths, primarily due to technical limitations. In these deeper environments, deformation - whether from natural events or human intervention - occurs alongside hot and pressurized hydrothermal fluids. These fluids significantly impact the strength and frictional properties of faults by facilitating or hindering various chemical reactions (Mironenko & Zolotov, 2012).

This study presents findings from an innovative experimental framework that combines a rotary shear apparatus (ROSA) with a specialized hydrothermal vessel (HYDROS). This integration allows for simulating the loading conditions and significant slip displacements typical of natural faults, alongside environmental parameters that mimic the seismogenic depths, characterized by hot, pressurized fluids. The natural case study focuses on an ancient seismogenic fault within the Atacama Fault System in Chile, which comprises altered rock types, specifically chlorite- and epidote-rich cataclasites, set in a continental crystalline basement of non-altered granodiorite. Results from week-long experiments on powdered samples indicate that in non-altered granodiorite, fault frictional healing does not increase as would typically be expected, contrasting with observations from cataclasites. Instead, granodiorite shows a decrease over time. Notably, the initial fluid chemistry is crucial in influencing the fault frictional healing response, with a significant shift observed in non-altered rocks when equilibrated fluids with different chemistry are present.

This decrease in fault frictional healing and how fluids change during the evolution of faults can have significant implications for the recurrence intervals of earthquakes and magnitude (increasing and decreasing, respectively) and the dynamics of the seismic cycle for both natural and human-induced earthquakes.

Dieterich J.H. (1972) - Time-dependent friction in rocks. J. Geophys. Res., 77, 3690-3697.

Mironenko M.V. & Zolotov M.Y. (2012) - Equilibrium-kinetic model of water-rock interaction. Geochemistry Int., 50, 1-7.

The role of strain rate and confining pressure in the rheology of Triassic Evaporites: implications for distributed seismicity within the seismogenic regime

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Keywords: earthquakes, laboratory experiments, rheology.

In the case of the Mw 6.5 2016 Norcia earthquake in central Italy, precise earthquake location reveals the coexistence of localized, on-fault seismicity and widespread distributed seismicity (DS), which occurs exclusively after the mainshock, up to several kilometers from the ruptured fault. Importantly, DS is located where the integration of surface geology and seismic reflection profiles identifies the presence of the Triassic Evaporites (TE), made of anhydrites and dolostones. Field geology and laboratory studies indicate that away from fault zones the rheology of TE is mainly ductile, implying an embrittlement mechanism to be activated after the mainshock. Moreover, the Coulomb stress change simulated after the Norcia mainshock highlights that the crustal regions that produced DS experienced an increment in strain rate.

To explore the role of strain rate on the rheology of TE, we conducted 15 triaxial rock deformation experiments on cylindrical TE samples with different fabrics: anhydrites, foliated anhydrites-dolostones and chaotic, high-dolostone content aggregates. A constant confining pressure of 10 and 20 MPa was applied to the samples, loaded up to failure at strain rates ranging from 10-4 to 10-6 s-1 to assess mode of failure and deformation style of TE. In most of the cases the experimental faults were reactivated, to investigate fault structure evolution and frictional stability at high shear strain.

All the samples exhibited brittle failure with associated stress drop. Upon rock failure, we observed a spectrum of fault slip behaviors ranging from slow (< 1 μm/s) to fast (> 1 mm/s) fault slip. We note that dynamic faulting occurred preferentially under low confining pressure, at elevated strain rate in dolostone-rich samples. Upon fault reactivation, we recorded fault slip instabilities, mainly for the same type of aforementioned conditions. Microstructural investigations revealed that the transition from slow fault slip to dynamic failure is linked to a shift from distributed damage to localized on-fault shearing. At high strain, samples that produced fault slip instabilities featured enrichment of dolostone within the fault slip zones, characterized by grain size reduction and intense shear localization.

Mechanical and microstructural evidences suggest that rheological embrittlement of TE is promoted by low confining pressure, high strain rate, and elevated dolostone content. The concurrence of these conditions likely facilitated the production of DS in the natural case. Mainshock-induced strain rate increase, fluid overpressure (reducing the effective pressure), and dolostone smearing along the fault slip zones may have triggered brittle failure of intact rocks and unstable reactivation of small faults. Our results shed light on the complex rheological control on a spatially and temporally variable brittle-ductile transition, which shapes the extent of the seismogenic regime of the Earth's crust.

Unveiling the preparatory phase of the 2023 MW 7.8 Kahramanmaraş earthquake: Insights from high-resolution seismicity and ML workflows

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Keywords: earthquakes, faults, preparatory phase.

Intermediate-term transient fault behaviors - ranging from seismic to aseismic slip - have been postulated as harbingers of large earthquakes, yet their detection remains challenging due to variability across sequences and limitations in monitoring resolution. In this study, we investigate the years-to-months deformation preceding the 2023 MW 7.8 Kahramanmaraş earthquake in Türkiye, focusing on transient seismicity and its potential implications for earthquake nucleation.

Using a conventionally derived seismicity catalog, we identify isolated spatio-temporal clusters of seismic events within a 65 km radius of the eventual rupture zone, embedded in a structurally complex fault network. These clusters, being active during the eight months leading to the mainshock, collectively contributed to an acceleration of seismicity and a localized decline in Gutenberg-Richter b-values, suggesting increasing stress and potential fault weakening.

To resolve finer-scale deformation patterns, we enhanced the seismicity catalog based on machine learning models spanning six years prior to the earthquake. This high-resolution analysis reveals intensified seismic activity along the Narlı Fault - a secondary structure within the East Anatolian Fault Zone and the location of the mainshock epicenter - beginning several months before the rupture. We also observe elevated background seismicity following the 2020 MW 6.8 Sivrice earthquake, possibly suggesting stress accumulation. These findings point to persistent damage-induced weakening and stress concentration and accumulation near the future rupture zone, especially within the fault volume bridging the 2020 and 2023 earthquakes.

To evaluate the detectability of these seismicity transients as potential precursors, we implemented an unsupervised machine learning framework. By extracting seismo-mechanical features for clustered events in space-time, the algorithm unveils discrete evolutionary stages of seismicity. Notably, a distinct class of long-lived, critically stressed event clusters emerges in the months preceding the mainshock - characterized by intensified spatio-temporal localization, elevated earthquake interaction, and anomalous seismic strain release - suggesting a detectable preparatory phase.

Our findings underscore the potentially critical role of high-resolution seismic monitoring combined with data-driven ML frameworks for identifying meaningful transient patterns. These approaches pave the way for objective, assumption-free classification of fault system behavior and hold promise for advancing operational earthquake forecasting.

Frictional healing of anhydrite faults imaged by ultrasonic waves

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Keywords: earthquakes, laboratory, friction.

The ability of faults to regain strength between earthquakes (fault healing) is crucial to understand the seismic cycle. In lithologically heterogeneous faults, variations in healing rates among rock types can cause local locking and elastic strain energy accumulation, potentially leading to earthquake nucleation. Anhydrite is a key component of the Triassic Evaporites, the seismogenic layer of central Italy, which hosted the 2016 Mw 6.5 Norcia mainshock. However, its complex mechanical behavior remains underexplored. Minor variations in effective pressure, strain rate, and temperature alter anhydrite's healing properties, rheology, and fault slip behavior.

We conducted dry and wet Slide-Hold-Slide (SHS) friction experiments on anhydrite gouge to assess its healing behavior. To inform mechanical data with the microphysical evolution of the fault, we used PZT sensors in transmission mode, which record ultrasonic wave (UW) propagation through the sample. Finally, mechanical and ultrasonic measurements were complemented by microstructural analyses.

Our results show that wet experiments are characterized by a higher healing rate ($\beta = 0.025$) with respect to dry ones ($\beta = 0.007$). In both wet and dry tests, fault healing follows a log-linear dependence with hold duration. Similarly, UW amplitude during hold periods increases log-linearly with hold time, at a significantly higher rate (Ψ) in wet conditions, exceeding a 20% increase relative to pre-hold values, compared to only ~3% increase in dry samples. Decreasing the apparatus stiffness, we observed the emergence of unstable slip only for wet tests and at low sliding velocities (≤ 1 μm/s). Microstructural analysis of wet samples reveals intense shear localization and grain size reduction within highly localized B-shear bands, along which a compressive foliation develops (S-planes), highlighting a semi-brittle deformation regime. Conversely, dry samples predominantly feature distributed deformation within multiple R-shear bands.

The observed differences between dry and wet experiments suggest that water-activated chemical processes play a major role in controlling the healing properties of anhydrite. This is supported by significantly higher values of Ψ in wet conditions. The log-linear increase in UW amplitude with hold time indicates that frictional healing is closely linked to fault microphysical processes that lead to an increase in grain contact stiffness, which appear to be more effective in the presence of water. We interpret that high healing rate of wet anhydrite, associated with local semi-brittle deformation, may promote the observed unstable fault slip at low slip rates, when inferred water-activated processes have enough time to operate by locking specific fault segments.

To better constrain these hypotheses, the relationship between frictional healing and elastic properties of anhydrite will be addressed through the extraction of elastic moduli from UW velocities.

Hydro-to-thermo-chemical reactions affect seismic slip of carbonate-hosted fault zone

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Keywords: carbonate fault, microstructures, deformation mechanisms.

The elastic energy released during an earthquake is mostly dissipated along the fault zone, with only a small portion converted into seismic waves. Laboratory experiments show that fault rock sheared at seismic slip rates experience a drastic reduction in their friction coefficient. This is connected to the activation of processes such as frictional heating and thermal pressurization whose effects contribute to the frictional strength reduction. Understanding the mechanisms controlling fault strength evolution at seismic slip rates is of paramount importance, since strength influences earthquake parameters, such as rupture propagation, stress drop and energy budget partitioning. In carbonate-hosted faults, the identification of seismic markers is challenging due to poor preservation and limited occurrence. In this context, field-to-microscale observations are essential to validate experimental data and refine models of earthquake mechanics. This study presents preliminary results from a carbonate-hosted fault, aiming to characterize the fault rock microstructures and constrain weakening processes. A systematic sampling was conducted along an intra-dolomitic normal fault striking approximately NW-SE, exposed on the eastern margin of the Agri Valley, Southern Apennine. The principal slip zone (PSZ) mainly consist of fine-grained cataclasites, with grain comminution increasing towards the principal slip surface (PSS). These carbonate cataclasites are locally intruded by thin, dark colored, fluidized ultracataclastic layers showing protrusions and flame-like-texture aligned with the sense of shear. A reddish altered layer often adjacent to the fluidized cataclasites exhibit textural features related to both brittle and fluid-assisted processes. Rarely, a discontinuous vein-like layer localizes next to the PSS. Backscattered images of the vein-like layer reveal an ultrafine calcite filled material containing micrometric relicts of dolomitic clasts. Adjacent to the PSS, this layer contains nanoparticles, vesicles, and distinctive chain-like nanostructures characterized by calcite nanoparticles linked by nanotubes.

Overall, the first results of this study suggest that both fluid- and thermo-assisted processes occurred along the studied fault zone. The microstructural and textural features of the observed products suggest a rapid formation, consistent with seismic slip rates. In detail, decarbonation took place only within the vein-like layer. Differently, fluidization processes affected broader portions of the fault zone, also suggesting their contribution to seismic slip. Preliminary conclusions are therefore consistent with the coeval and confined activation of thermo-to-fluid processes, which likely took place within dissimilar portions of the fault zone. Such a multi-process deformation mechanism could have acted as a multi-effects trigger responsible for fault strength reduction in carbonate-hosted normal fault zones.

Identifying fault surface segmentation patterns with unsupervised learning applied to 3D earthquake hypocenter distributions

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Keywords: earthquakes, faults, seismic hazard.

Understanding the hierarchical segmentation of active fault surfaces is crucial for seismic hazard assessment as interactions between segments control how earthquakes initiate, propagate, and terminate along a fault system. This task, however, remains particularly challenging, especially in areas where detailed geological or geophysical data are lacking. To contribute to this issue, we propose an automated workflow to derive fault surfaces and their hierarchical segmentation from the spatial distribution of earthquake hypocenters (Piegari et al., 2024). The method combines two density-based clustering algorithms, DBSCAN and OPTICS, with Principal Component Analysis (PCA). DBSCAN is first applied to identify first-order clusters, corresponding to the densest and most connected regions of seismicity, interpreted as main fault surfaces. Within each of these, OPTICS further detects nested, higher-order clusters, illuminating potential fault segments within the fault surface. PCA is then used to analyze the geometry of each cluster, distinguishing between planar features associated with faults and more distributed, uncategorized seismicity. The workflow operates at multiple spatial scales, with the largest scale representing the longest patterns of dense seismicity and the smallest limited by earthquake location errors. We demonstrate the effectiveness of this approach on earthquake catalogs from Italy, Taiwan, and California, encompassing faults with diverse kinematics. Comparison with focal mechanism solutions confirms the reliability of the reconstructed fault planes and segments. This methodology provides an unbiased and scalable tool for fault surface segmentation analysis, supporting improved seismic hazard models in data-limited settings.

Piegari E. et al. (2024) - Illuminating the Hierarchical Segmentation of Faults Through an Unsupervised Learning Approach Applied to Clouds of Earthquake Hypocenters. Earth and Space Science, 11(10), e2023EA003267, https://doi.org/10.1029/2023EA003267.

Shallow depth fault hosting evidence for past earthquake ruptures propagating through sediments: example from the Crotone Basin, South Italy

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Keywords: earthquake geology, coseismic deformation, shallow burial conditions.

The unstable seismogenic zone is the locus of most earthquakes and is located between 5 and 35 km of depth. Its uppermost part (< 5 km) is considered seismically stable crosscutting low cohesion rocks and water-saturated sediments. Nevertheless, many earthquakes nucleate at depths shallower than 5 km in different geodynamic settings and kinematic regimes. Such shallow seismicity could represent an additional threat to be accounted for in earthquake risk assessment.

We present the results of a multidisciplinary study dealing with shallow coseismic deformation and earthquake propagation recorded within the fault core of an extensional fault zone. The studied fault zone is exposed along the Vitravo Creek canyon, in the Crotone Basin, South Italy and affects high porosity, Plio-Pleistocene siliciclastic rocks. The fault displacement reaches ~50 m and deformation of high porosity rocks is achieved by development of deformation bands and subsidiary faults composing the hanging wall and footwall damage zones. The master slip surface is decorated with a 2-3 cm-thick dark gouge. The gouge is continuous and isopachous along the entire outcrop exposure and has locally been injected into brittle fractures affecting the calcite cemented fault core. Subsidiary, thinner (~1 mm-thick) gouges are present at a few cm of distance from the main one in the hanging wall block. Microstructural and granulometric analyses conducted on the dark gouge pointed out a severe cataclastic particle size reduction and a marked gradient in clast comminution from the footwall towards the hanging wall side. XRD mineralogical analysis performed on the < 2 μm size fraction of the dark gouge, revealed high percentage (~60%) of illite in the illite-smectite mixed layers, suggesting deformation temperature up to 100-120 °C. XRD analyses conducted on host rock, deformation bands and subsidiary faults along the entire fault zone returned estimated deformation temperatures of < 50 °C, which are compatible with the calculated sediment overburden (< 800 m). The anomalous and localized increase in temperature within the dark gouge has been linked with flash heating processes likely related to coseismic deformation under shallow burial conditions. Frictional experiments run on host sand samples collected along the fault zone allowed to constrain their mechanical behavior at different slip rates (aseismic and coseismic) and under different water contents (dry vs water damped). The hanging wall sand showed a slip-weakening behavior compared to the marked slip-hardening displayed by the footwall sand. According to our results, the hanging wall sand was more prone to promote the earthquake nucleation and seismic propagation up to the surface.

The systematic adoption of a combined field and laboratory-based approach to several fault zones and fault systems could enhance and improve the earthquake risk and hazard assessment in Calabria region.

Rheological control on distributed aftershock activity: insights from the Mw 6.5 Norcia seismic sequence

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Keywords: triassic evaporites, distributed seismicity, rheology.

The spatio-temporal evolution of seismicity provides insights into the brittle deformation of the Earth's crust. During a seismic sequence, the spatial distribution of aftershocks typically reveals the structural architecture of the fault zone activated during the mainshock. However, within the seismogenic crust, seismicity is not necessarily exclusive of the mainshock rupture plane. In the case of the M_w 5.9 and M_w 6.5 2016-2017 Visso-Norcia (Central Italy) seismic sequence, widespread distributed seismicity (DS, Mw < 4) has been recorded in a large volume mostly located down-dip of the earthquake rupture plane in the depth range of 4-11 km. Here, seismic reflection profiles identify the presence of Triassic Evaporites, TE, a geological formation composed of anhydrites and dolostones. Field observations show that, away from the major brittle faults, TE deformation consists of a background ductile deformation interspersed with brittle processes in the form of distributed failure and folding of the anhydrites associated with boudinage hydro-fracturing and faulting of dolostones.

In this work we studied the details of DS to capture the structural features of distributed seismicity and infer the rheology of this portion of the seismogenic layer.

Through the construction of a series of seismological cross sections oriented perpendicularly to the strike of the mainshock rupture plane, we identified and isolated two main types of DS: (1) diffuse, non-localized seismicity, and (2) localized seismicity, illuminating kilometers-long structures with different orientations. For each structure we investigate the scaling between the cumulative seismic moment ∑M0 released and the equivalent circular fault area activated, to infer their rheological properties.

The selected localized seismicity shows three different temporal evolutions of the seismicity rate, suggesting three different seismological behaviors:

- Mainshock-independent Omori-like decay,
- Swarm-like activity, and
- Omori-like decay from the Norcia Mainshock.

We interpret the occurrence of DS as the result of the embrittlement of the evaporitic layer induced by an increase of strain rate following the Norcia mainshock. Coulomb stress changes simulated after the Norcia mainshock suggest an increase in strain rate within rock volumes where DS is recorded. This is supported by recent laboratory experiments showing that a switch from ductile distributed deformation to brittle, localized faulting occurs for an increase of strain rate, and/or a decrease of effective pressure (a proxy for fluid overpressure in nature). Moreover, we observe that the ∑M0 scales with r^2 rather than r^3, suggesting that some deformation is accommodated aseismically in agreement with the ductile behaviour of TE.

Our results suggest that the aftershock distribution during a seismic sequence can be strongly controlled by the rheology of the lithologies contained within the seismogenic crust.

Hybrid FEM-Peridynamic modelling of supershear earthquake ruptures

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Keywords: supershear, peridynamics, saturated porous media.

During earthquakes, seismic ruptures propagate (V_r) along faults as mode II-III cracks, approaching the shear wave speed V_s (i.e., *sub-Rayleigh* or $V_r \sim 0.9\ V_s$), or, in at least 15% cases, at V_r faster than V_s (i.e., *supershear* or $V_r \sim V_s\sqrt{2}$) (Bao et al., 2022). Since ground shaking increases with rupture speed, the transition from sub-Rayleigh to supershear speeds is critical in seismic hazard studies. This transition may occur (1) directly, due to dynamic stress perturbations associated with stress and strength heterogeneities along the fault, presence of fault step-overs and damage zones, etc., or (2) in-directly, where the stress peak ahead of the main crack tip (mother crack) nucleates a secondary crack (daughter crack) once the local fault strength is exceeded (Burridge-Andrews model). Here we employ a newly-conceived 2-dimensional hybrid Finite Element Method and Peridynamic (FEM/PD-2D) model to simulate crack propagation and investigate the transition from sub-Rayleigh to supershear in dry and fluid-saturated media, where the Finite Element Method is used to simulate fluid flow, while Peridynamics is used to describe solid deformation. The model also incorporates a novel bond failure criterion based on critical rotation deformation (i.e., deflection angle of the Peridynamic bonds before and after shear deformation) for mode II fracture propagation. First, we validate the FEM/PD-2D model against previous results from (1) numerical simulations with ABAQUS in (Yolum et al., 2021), and (2) physical experiments with PMMA in (Svetlizky et al., 2016). In both cases, the FEM/PD-2D model reproduces rupture propagation, the transition to supershear with the emergence of shear Mach waves. Subsequently, we apply the FEM/PD-2D model to explore rupture propagation along both dry and fully saturated media under shear loading. Supershear crack speeds and the emergence of shear Mach cones are observed in both the dry and fluid-saturated cases. Supershear rupture can be achieved through either the in-direct (Burridge-Andrews mechanism) or a direct transition. Notably, the presence of the fluid phase enhances the sub-Rayleigh to supershear transition due to poroelastic effects at the rupture front. Finally, we adopt the FEM/PD-2D model to simulate crack propagation in dry and saturated porous media consisting of rock. The FEM/PD-2D model shows powerful potential in application of rock fracture modelling. Given the relative high frequency of the damaging "supershear" earthquakes, the findings from this model, beyond their implications for hazard assessment, may also explain the deformation processes and features associated with earthquakes, including the formation of hundred-meter-thick rock damage zones adjacent to seismogenic faults.

Bao H. et al. (2022) - Global frequency of oceanic and continental supershear earthquakes. Nature Geoscience, 15(11), 942-949, https://doi.org/10.1038/s41561-022-01055-5.

Svetlizky I. et al. (2016) - Properties of the shear stress peak radiated ahead of rapidly accelerating rupture fronts that mediate frictional slip. Proceedings of the National Academy of Sciences, 113(3), 542-547, https://doi.org/10.1073/pnas.1517545113.

Yolum U. et al. (2021) - Intersonic shear crack propagation using peridynamic theory. International Journal of Fracture, 228(1), 103-126, https://doi.org/10.1007/s10704-021-00520-3.

From stick to slip. Novel opportunities in experimental earthquake mechanics for imaging the earthquake preparation stage

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Keywords: earthquake mechanics, deformation patterns, friction.

Mapping displacements and stresses before and after dynamic slip instabilities is critical to identifying where and how rupture nucleates and localizes. Along with a deep understanding of the evolution of slip and coseismic slip rates, these observations are key to constraining physical models of earthquake processes and seismic hazard. Recent developments in experimental earthquake mechanics now offer the ability to simulate rupture propagation along extended fault surfaces under realistic boundary conditions (e.g. McLaskey & Yamashita, 2017).

Large-scale experiments simulate rupture propagation on a number of points interacting each other via elastic forces. These experiments provided valuable insights into the propagation of seismic ruptures, replication of aftershock-like behavior (Cebry et al., 2022) and but not limited to, on the effect of normal stress heterogeneities on rupture sequences as revealed by recent studies on PMMA (e.g. Cebry et al., 2023).

In this context we present MEERA (Mechanics of Earthquakes and Extended Ruptures Apparatus), a novel multi-axial testing machine installed at the HPHT Rock and Earthquake Mechanics Laboratory (INGV). MEERA applies controlled shear and modulated normal loads (up to 20 MPa) on large cement blocks (300 × 80 × 45 mm³), with feedback control on displacement (up to 30 mm), force (up to 150 kN for tangential and up to 100 kN for normal), and slip rate (up to 40 mm/s). Our experiments aim to reproduce dynamic instabilities, visualize pattern of deformation during the preparation stage of slip events and eventually, resolve the spatial and temporal evolution of fault slip.

To this end, we employ digital correlation image techniques on high-resolution camera similar to the laboratory analogue of air- and spaceborne remote sensing techniques previously developed by Rubino et al. (2015). The surficial pattern is combined with embedded Bragg fiber-optics sensors (ca. 5 mm away from the fault) and acoustic emission monitoring. This multi-sensors approach enables unprecedented visualization of fault zone processes, including aseismic deformation and microseismicity.

Ongoing work focuses on identifying preparatory deformation patterns and their link to the final size of rupture events in the framework of the ERC projects St.G. FORESEEING and and Syn. FEAR. Ultimately, we aim to detect early signals that distinguish between the precursors of small and large earthquakes for possible application to early warning systems.

Cebry S.B.L. et al. (2022) - Creep fronts and complexity in laboratory earthquake sequences illuminate delayed earthquake triggering. Nat. Commun., 13, 6839, https://doi.org/10.1038/s41467-022-34397-0.

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Seismicity and Vp and Vp/Vs models around the Mefite d'Ansanto deep-CO_2 degassing site (Southern Apennines, Italy)

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Keywords: earthquakes, Southern Apennines, deep CO_2 Earth degassing.

Mantle-derived fluids play a primary role in the generation of large upper crustal earthquakes in extensional domains. Here, we focus on the Mefite d'Ansanto degassing site, the largest low-temperature non-volcanic deep-CO_2 emission site in the world (about 2000 tons per day), located at the northern tip of the Mw6.9 1980 Irpinia faults in the Southern Apennines (Italy). The area, characterized by high heat flow and pervasive CO_2 rich fluids circulation, experienced strong historical earthquakes (M6+) but it is characterised by low background seismic rate, with respect to the nearby Sannio and Irpinia regions.

To investigate this key-sector of the Southern Apennines, within the multidisciplinary FURTHER project (https://progetti.ingv.it/en/further), a collaborative initiative exploring the role of fluids in seismogenesis within the Southern Apennines, we collected high-quality microseismicity data during a two-year dense temporary passive survey (May 2021 to May 2023). Starting from about 300 manually picked earthquakes, we applied a template-matching algorithm to detect low-magnitude seismicity. We computed a best fit 1D Vp velocity model of the area through a non-linear technique, and 1D earthquake locations using the probabilistic non linear location method *NonLinLoc*. The final catalog is composed of about 1300 earthquakes ($-0.7 < ML < 3.0$). Most of the seismicity has small magnitude ($ML < 1$), confirming the low seismic rate of this area compared to the adjacent regions, and occurs in small clusters (sometimes along small faults) characterized by either short-lived or sustained seismic activity. We also computed a new 3D Vp and Vp/Vs seismic tomography model of the area together with full moment tensor solutions for the largest magnitude events.

The combined interpretation of Vp and Vp/Vs velocity models, seismicity distribution and full moment tensor solutions (i.e., double-couple *vs* non-double-couple component) helped us to investigate the relationship between seismicity, crustal structure and fluid pressure in this crucial sector of the Southern Apennines seismic belt.

Spatio-temporal variations of pore pressure during earthquakes: case studies using well data from Southern Italy

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Keywords: pore pressures, earthquakes, exploration wells.

Spatio-temporal variations in subsurface pore pressure are crucial for understanding geomechanics and seismicity. Pore pressure, which is exerted by fluids within porous rocks, is influenced by both geological and anthropogenic factors. Traditionally, research has focused on the relationship between pore pressure and induced micro seismic events (e.g., Terakawa et al., 2012), with changes in pore pressure often inferred from seismic data and numerical modelling (e.g., De Matteis et al., 2021). Nonetheless, studies utilizing exploration well data remain relatively underexplored. Analysing pressure regime from wells drilled before, during, and after significant seismic events could provide valuable insights into transient effects of fluid flow. This study aims to examine whether large earthquakes induce changes in pore pressures that can be recorded by exploration wells. Specifically, we investigate if accumulated elastic strain in the Earth's crust, released as seismic energy during an earthquake, induces fluid flows in porous media observable in the borehole data. The study utilizes three datasets: borehole data from the ViDEPI project, significant earthquakes from the parametric catalogue of Italian earthquakes (CPTI15; Rovida et al., 2020), and ground shaking maps (Oliveti et al., 2023). In particular, the Historical Shake Maps combine macro seismic data, instrumental data, historical sources, and ground motion modelling to reconstruct ground shaking for past earthquakes. The available finite fault representations enhance the accuracy of the shaking estimates. Regarding well data, this information comes from expired mining titles stored at UNMIG since 1957. The applied methodology includes: 1) a "cascade procedure" with a proximity criterion for data selection, assessing the influence distance between boreholes and earthquake epicentres; 2) pore pressure calculation, using methods commonly adopted by the oil industry; 3) comparison between pressure variations and earthquake over time, highlighting potential causal effects. This study focused on earthquakes (Mw > 6) that occurred between 1950 and 2000, identifying five major epicentral areas from the Friuli region to Sicily. Among the various criteria for selecting well data, a quantitative physical criterion was preferred, focusing on the extension of areas affected by ground shaking. Wells were categorized into four zones based on shake intensity: no significant effects at the wells (intensity < 6), low effects (6-7), moderate effects (7-8), and strong effects (intensity > 8). Three earthquakes had maps showing intensity and peak ground acceleration, with well data available only for two of them: the Irpinia and Irpinia-Lucania regions. This preliminary study provides new insights into direct measurements of pore pressure related to seismicity, with wells extending from 1 to 6 km in depth. The findings offer critical perspectives on geomechanical and seismic phenomena, potentially enhancing the understanding gained from indirect geophysical data.

De Matteis R. et al. (2021) - Pore fluid pressure imaging of the Mt. Pollino region (southern Italy) from earthquake focal mechanisms. Geophysical Research Letters, 48, e2021GL094552, https://doi.org/10.1029/2021GL094552.

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Terakawa T. et al. (2012) - High fluid pressure and triggered earthquakes in the enhanced geothermal system in Basel, Switzerland. Journal of Geophysical Research, 117, B07305, https://doi.org/10.1029/2011JB008980.

Rupture variations and seismic cycle complexities arise from structural and frictional heterogeneities: insights from large laboratory faults

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Keywords: seismic cycle, seismic rupture, laboratory experiments.

Models of earthquake recurrence are inevitably based on simple ideas of a threshold frictional failure stress that is constant or varies slightly based on the factors such as recent recurrence interval and dynamic stressing. Such models are based on laboratory results for geometrically simple faults and carefully controlled conditions where friction obeys simple laws related to contact junction aging (e.g., fault healing) and fault slip velocity. These models yield estimates of earthquake recurrence based on elapsed time from the previous event and slip or stress drop of the previous event (e.g., time-predictable or slip predictable models, respectively). Here, we show that fault zone heterogeneity and interactions between neighboring slip patches on a laboratory fault can produce more complex laboratory earthquake dynamics. Our results are coherent with previous works, primarily theoretical, showing complexity. We extend those works significantly via connections to models of fault healing and local measurements of aseismic fault slip during laboratory earthquake nucleation prior to dynamic rupture. We show that both off-fault fractures and self-generated structural heterogeneity produce complex seismic cycles and rupture patterns. Seismic cycle complexity occurs in tandem with expected behaviors related to the transition from aseismic creep to dynamic failure. For conditions far from the stability boundary where elasto-dynamic rupture occurs or, at the other extreme, aseismic slip occurs, system behavior tends to be relatively simple. For these conditions, fault healing and earthquake recurrence interval vary systematically with slip velocity, whereas for conditions near the stability boundary complex behaviors overprint expectations from rate and state friction.

Frictional Stability of Gouges from Well IDDP-1 in Response to Liquid–Vapor Water Phase Transitions at Krafla, Iceland

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Keywords: friction, induced seismicity, geothermal systems.

Understanding fault frictional properties in deep reservoirs is crucial for the safe exploitation of geothermal energy. Here, we investigate the influence of water on fault friction (frictional strength (m_{ss}) and fault frictional healing (Δm)) under conditions of the volcanic geothermal system of Krafla (Iceland). We use a rotary-shear apparatus equipped with a hydrothermal vessel to simulate geothermal conditions and test simulated fault gouges (< 125 μm) derived from drill cuttings of the well IDDP-1. The materials include: (1) altered basalts dominated by chlorite (338 m), chlorite-epidote (642 m), and epidote-actinolite (1222 m and 1686 m); (2) basaltic dykes with little alteration (1970 m); (3) granophyre (2066 m); and (4) rhyolite (2104 m).

Friction experiments were conducted at subseismic slip rates (3-100 μm/s) under temperature (T), pore fluid pressure (P_f), and loading conditions (σ_n^{eff}) representative of the dual system in Krafla: an upper reservoir at liquid conditions (T = 170 ˚C, P_f= 10 MPa, σ_n^{eff}= 10-30 MPa) at depths < 1 km, and a lower reservoir at boiling conditions (T = 300-350˚C, P_f= 10 MPa, σ_n^{eff}= 30-50 MPa) at depths of 1-2 km. Key findings include:

- Shallow depth gouges (342 m and 642 m) tested at upper reservoir conditions show stable sliding with velocity-weakening behavior and low Δm (< 0.02);
- Intermediate depth gouges (1222 m) tested at upper reservoir conditions show stick-slip behavior (minor stress drop) and increased Δm (< 0.04), while under lower reservoir conditions the are highly unstable, with pronounced stress drops in liquid and small stress drops in vapor water, and with high Δm (< 0.1);
- Great depth gouges (1686 m, 1970 m, and 2066 m) tested at lower reservoir conditions show stick-slip regardless of the water state (large stress drop in liquid and small stress drop in vapor water) with high Δm (< 0.1);
- To explore the influence of water phase on fault stability, we performed three experiments on the 1970 m gouge, with a constant slip rate of 10 μm/s while cycling between liquid and vapor water. These were carried out under: (1) T = 350 ˚C, P_f= 10-30 MPa, σ_n^{eff}= 50 MPa, (2) T = 100-350˚C, P_f= 10 MPa, σ_n^{eff}= 50 MPa, and (3) T = 300-350˚C, P_f= 10 MPa, σ_n^{eff}= 10-50 MPa. The results show larger stress drops in liquid than in vapor water, especially under higher σ_n^{eff} (30–50 MPa), proving the destabilizing effect of liquid water.

Microanalyses (FESEM, μXRPD) of the deformed gouges reveal similar microstructures across all conditions, with deformation localized in a continuous slip zone with sub-angular grains (size <5–10 μm) embedded in an ultrafine chlorite- and amorphous material-rich matrix.

To conclude, the physical state of water plays a critical role in controlling fault frictional behavior in geothermal systems. Our findings suggest that the reinjection of liquid water into deep geothermal reservoirs should be done with caution, as transitions from vapor to liquid water may enhance fault instability and potentially trigger seismicity.

S8.

Cross-disciplinary insights into geodynamic processes: from the mantle to the surface

Conveners and Chairpersons

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The role of extensional to transtensional tectonics in the sedimentation of the Ranzano Formation in the Tortona and Voghera Apennines (Northern Apennines, NW Italy)

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Keywords: Northern Apennines, Epiligurian Units, transtensional tectonics.

Different types of sedimentary basins are associated with convergent margins and they are mainly distinguished according to their position along the thrust belts. Among the different types, wedge-top basins develop onto the frontal part of the advancing orogenic wedges and their large-scale architecture, basin margins, and depozone migration are influenced by the convergent dynamics and kinematic history of the underlying thrust-belt. However, extensional and transtensional faults can usually contribute to small-scale modifications of the internal basin-physiography, for example controlling the main depozones and the delivery of the coarse-grained sediments. Thus, understanding the contribution of extensional and transtensional tectonics during wedge-top basins filling might play a crucial role to reconstruct the wedge-top basin geometries with particular focus on the distribution of potential coarse-grained reservoirs for industrial applications (e.g., hydrocarbon research, CO_2 storage, water reserve).

In the Northern Apennines (NW Italy). the middle Eocene – Miocene Epiligurian Units are interpreted in literature as the filling of a wedge-top basin formed on top of the advancing Northern Apennines orogenic wedge. We present new geological mapping data combined with detailed stratigraphic, biostratigraphic and structural analysis from the Epiligurian Units in the Tortona and Voghera with the aim to reconstruct the role of the tectonics during the sedimentation. In this sector, these units are mainly composed of the shaly-marly Monte Piano Formation (middle – late Eocene), the turbiditic succession of the Ranzano Formation (late Eocene – Oligocene), and the slope marls of Antognola and Contignaco Formations (late Oligocene – early Miocene). These successions crop out in the hanging-wall of a regional-scale thrust zone where are deformed by an NE- to ESE-striking syncline that is cut by NE-SW to N-S striking transtensive to normal faults that are unconformably sealed by the Antognola and Contignaco Formations. The internal thickness and lithofacies variations of the Ranzano Formation in the different fault-bounded blocks document that the main depozones and the flux of sediments in the turbiditic basin was influenced by the transtensional-normal faults. This case study prove that along convergent margins extensional and transtensional tectonics can significantly control the sedimentation, contributing to the dynamic evolution of the associated sedimentary basins.

Rheological response to magma pressurization at Mt. Etna volcano: simulating geophysical observations via thermomechanical modeling

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Keywords: Etna's sliding flank, magma pressurization, geodynamic modeling.

Mount Etna lies on the northeastern coast of Sicily in the central Mediterranean and is one of the most active and hazardous stratovolcanoes in the world. Its southeastern flank is gradually sliding toward the Ionian Sea, a movement driven by gravitational spreading and tectonic forces that can lead to crustal fracturing and the formation of new magma pathways. In previous work, we modeled flank sliding by considering only rheological properties and tectonic forces. We now extend our approach by including the role of magma pressurization, which is thought to accelerate the sliding process.

To simulate ground deformation, we used the 3D thermomechanical finite-difference code LaMEM (Lithosphere and Mantle Evolution Model; Kaus et al., 2016). We constructed the model geometry using the *GeophysicalModelGenerator.jl* package and real topographic data, all implemented in the Julia programming language (Kaus et al., 2024). Geological structures were defined based on geological maps and seismic velocity models, with rock properties assigned from laboratory measurements and typical upscaled values used in geodynamic simulations. The model focuses on a brittle upper crust and a southeastern flank that is mechanically decoupled from surrounding structures by weak rock zones. These are represented by major fault systems: the Pernicana Fault to the north and the Mascalucia-Tremestieri, Fiandaca-Pennisi, and Gravina Faults to the south – underlain by a thrust sequence of the Apennine-Maghrebian Chain. In particular, the clay-rich materials atop this sequence aid decoupling the flank and support its sliding.

We successfully modeled the ground deformation of Mount Etna's southeastern flank during a period of volcanic quiescence, comparing the results with GPS data. Different model geometries, ranging from simpler to more complex configurations, were tested and quantitatively evaluated by estimating the coefficient of determination. We explored various rock parameter values, including brittle, semi-brittle, and ductile settings, and found that ductile rheologies provided the best fit. Our current modeling efforts focus on introducing magmatic activity and improving alignment with seismic and GPS observations from 2018. We continue to apply a ductile rheology within the general model framework, while testing various rock parameter values and different geometries for the magma reservoir.

Kaus B.J. et al. (2016) - Forward and inverse modelling of lithospheric deformation on geological timescales. In: Binder K., Muller M., Kremer M., Schurpfeil A. (Eds), Proceedings of nic symposium, John von Neumann Institute for Computing (NIC), NIC Series, 978-983, http://hdl.handle.net/2128/9842.

Kaus B.J. et al. (2024) - Geophysicalmodelgenerator. jl: A julia package to visualise geoscientific data and create numerical model setups. Journal of Open Source Software, 9, 6763, https://doi.org/10.21105/joss.06763.

Assessing how convergence rate, lithospheric thickness and surface processes affect subduction dynamics with 2D thermomechanical numerical modelling

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Keywords: subduction, orography.

Despite numerical modelling is widely used to investigate subduction dynamics, the relative contribution of convergence rate, lithosphere rheology and erosion-driven surface mass redistribution, in affecting the overriding plate topographic evolution and its overall strain remains elusive. This work investigates the behaviour of the overriding continental plate during ocean-continent subduction by an extensive parametric study on key physical parameters using a 2D fully coupled thermomechanical and landscape evolution numerical model. The examined parameters include the convergence rate, different crust, mantle and thermal lithospheric thicknesses, and erosion rates, also accounting for asymmetric orographic effects.

Our modelling results show that a fast convergence velocity (5 cm/yr) and a thick sub-continental lithospheric mantle promote compression of the overriding continental plate in the initial stages of subduction, when the slab dip angle is gentle, and back-arc extension during advanced stages. Conversely, a slow convergence velocity (1 cm/yr) and a thin sub-continental lithospheric mantle promote widespread extension since the initial stages of subduction, with wide back-arc extension. However, erosion and orographic effects can drastically change the subduction dynamics and associated overriding plate strain distribution, with effects on the location, size and fate of continental fragmentation due to back-arc extension and rifting (e.g., Sternai et al., 2021). Fragmentation of the overriding continental plate can produce microcontinents whose fate can change in response to the investigated parameters. This extensive parametric study highlights hitherto unrecognized dynamics such as erosion-induced microcontinent subduction, with strong implications for plate kinematic reconstructions and our current understanding of tectonics-climate interactions.

Sternai P. et al. (2021) - Effects of asthenospheric flow and orographic precipitation on continental rifting. Tectonophysics, 820, 229120, https://doi.org/10.1016/j.tecto.2021.229120.

Pressurized magma storage in radial dike network beneath Etna volcano: evidence from P-wave anisotropic imaging

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Keywords: Etna, seismic anisotropy, stress state.

Investigating crustal stress beneath volcanoes is critical to understanding the dynamics of eruptions. To this end, seismology represents a powerful monitoring tool. The opening of fluid-filled fractures due to the interplay of different stress sources produces elastic anisotropy within the crust, affecting the propagation of seismic waves. Here we use probabilistic imaging for the inversion of P-wave travel-times to map elastic anisotropy of the magmatic system beneath Mt. Etna (Italy). These images provide localized information about fracture orientations and stress below this active volcano. Comparing inferred stress with independent observations and geodynamic modeling, we show evidence of a pressurized magma storage in a radial dike network between 6 and 16 km depth under the volcano. The radial network of vertical dikes constitutes a system of oriented pathways for the upward migration of magma from the depths, leading to eruptive activity from the summit craters and lateral vents at Mount Etna.

Normal faulting and hydrothermal dolomitization during the Pangea breakup in the southern Adria domain (Southern Italy)

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Keywords: hydrothermal dolomitization, normal fault zones, Pangea breakup.

Shallow crustal normal fault zones in carbonate successions are deformation structures that control subsurface fluid migration, localization, and fluid–rock interaction. These zones, characterized by fault-controlled fracturing and brecciation, can act as efficient conduits for hydrothermal fluids. The interaction between these fluids and the fractured carbonate rock matrix induces significant changes in the mineralogical and mechanical properties of the fault zone. In particular, mineral precipitation and cementation can strongly influence rock strength, and porosity evolution, with important implications for fault healing mechanics, reservoir quality, and ore deposit development.

This study presents, for the first time in the southern Apennines (southern Italy), evidence of fault-driven hydrothermal dolomitization during the Late Triassic rifting event that affected the western Adria Plate. We investigated saddle dolomite formation in Norian dolomites exposed in the western Matese Massif, focusing on dolomite breccias associated with N–S and NNW–SSE striking normal faults. These structures include layers of mature cataclasites made of angular clasts within a highly porous matrix, intersected by veins, and surrounded by mosaic and chaotic breccias. The breccias consist of angular clasts of host rock dolomite, formed by early marine replacive dolomitization of shallow-water carbonates, engulfed by coarse (~500 μm) saddle dolomite cement. Two distinct saddle dolomite phases were identified: SD1, yellow and inclusion-rich, forming a rim around clasts; and SD2, euhedral, exhibiting well-defined zoning with a transition from cloudy to limpid crystals. The saddle dolomite texture, along with decreasing $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values, suggests precipitation at temperatures of 100–120 °C from fluids likely influenced by magmatic sources. U–Pb dating of the dolomite cement indicates Late Triassic crystallization ages of approximately 217.0 ± 6.6 Ma and 206 ± 13 Ma. Additionally, the ferroan dolomite cement hosts minor hydrothermal minerals, including quartz, fluorite, and apatite.

These findings suggest that brecciation and hydrothermal dolomite cementation were linked to normal fault activity during the breakup of Pangea, contributing to the separation of the southwestern Eurasian margin from the Adria Plate. Furthermore, the observed textures and mineral assemblage provide insights into the structural evolution and fluid-rock interaction within normal fault zone during Early Mesozoic rifting in the southern Adrian domain.

Deciphering Eastern Adria's Mesozoic Tectonics: Alpine Tethys Kinematics and Rifted Margin Structure

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Keywords: Adria, Tethys, plate kinematics.

The Alpine Tethys and its Mesozoic rifted margins play a crucial role in understanding the geodynamic evolution of the region to the East of the Adria block(s). Despite advances in kinematic reconstructions of rifted margins, challenges persist in reconciling Iberian block motion with circum-Adriatic geology. Recent studies highlight the importance of intracontinental strike-slip corridors in defining continental block motion, as well as the need to restore rift domains using present-day analogs. This study integrates offshore seismic data, stratigraphic records, and kinematic models to propose a revised reconstruction of the continental blocks to the East of Adria, emphasizing the Alpine Tethys' polyphase rifting history. We demonstrate that: (1) rifting propagated westward from the Ionian to the Alpine Tethys and Pyrenean systems, (2) strike-slip corridors segmented the Tethyan margins, and (3) mantle exhumation and oceanic compartmentalization influenced later subduction dynamics. By synthesizing data from the Alps, Hellenides, and Carpathians, we constrain the Triassic–Cretaceous evolution of the Eastern Mediterranean, revealing competing geodynamic controls from Atlantic opening and Tethyan subduction. Our findings provide a refined framework for understanding the Eastern Adria's complex Mesozoic tectonics.

Tracing pre-orogenic origins: a multidisciplinary approach to the North Calabria Liguride Ophiolites (Southern Apennines, Italy)

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Keywords: ophiolite, OCT, Mesozoic Tethys.

The North Calabria Liguride Unit (NCLU) in southern Italy preserves remnants of the Jurassic Alpine Tethys, yet its pre-orogenic geodynamic setting and paleogeographic position remain debated. We present an integrated workflow combining field geology, petrology, geochronology, and plate reconstructions to constrain the origin of these ophiolites. Key findings indicate an ocean-continent transition (OCT) setting, evidenced by: (i) MORB basalts sealing tectonic contacts between depleted mantle and continental crust; (ii) Cr-rich mantle-derived fluids in continental fault rocks; and (iii) amphibolites and granulitic metapelites linked to pre-rift lower crust. Architectural similarities with the Tasna OCT and Sardinian margin analogues suggest a distal Sardinian position, conjugate to the Err-Platta OCT. While non-unique, this reconstruction provides a template for interpreting dismembered ophiolites in collisional orogens.

The IODP Exp. 402 overview and properties variability at the Continent – Ocean – Transition

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Keywords: extension, mantle exhumation, heterogeneity.

In spring 2024, IODP Exp. 402 was carried out in the Tyrrhenian basin, one of the youngest back-arc basins in the Mediterranean (Middle Miocene – present), with the aim of drilling and analyzing in detail the mantle exhumation process. Since the mantle has been drilled only in few other places in the world, due to the enormous difficulty of reaching and recovering it, its shallow depth in the Tyrrhenian Sea offers an exceptional opportunity to study the exhumation process and its interaction with fluids/melts, the timing and rate of exhumation and the lateral variability of its properties.

The opening of the Tyrrhenian Basin was favored by continental thinning, realized through a series of conjugate normal and listric faults, associated with the ESE-SE retreat of the subducting slab and the progressive eastward migration of the Apennine orogenic system. The central Tyrrhenian basin, specifically the Vavilov basin, is bounded by two conjugate margins that are represented by the Campania and Cornaglia terraces, which in turn are flanked by thinned continental crust. Therefore, the Tyrrhenian is the ideal place for studying the continent-ocean transition in back-arc setting.

During the IODP Exp. 402, 6 sites were drilled (Zitellini et al., 2025), two located on the conjugate margins and four in the deep central basin. Three of these four sites successfully recovered the peridotitic mantle rocks and young granitoid rocks (Poulaki et al., under revison) interlayered within the peridotites. The total 925 m of recovered sediments and rocks captured the transition from thinned continental crust to exhumed mantle. These sediments and rocks exhibit a wide range of petrological, lithological, chemical and physical properties. The mantle shows a significant heterogeneity (Sanfilippo et al., 2025), both laterally and with depth; and the age of sediments covering the mantle becomes younger toward north, suggesting that the exhumation occurred at different times or phases. While the conjugate margins, Cornaglia and Campania terraces, are characterized by the presence of Messinian evaporites that show a variability in thickness and facies likely controlled by basin morphology and by differential sedimentary supply from the nearby continental sources. Finally, the Pliocene-Quaternary sedimentary sequence that fills the entire basin shows a remarkable variability in the oceanic domain when compared to the conjugate margins. These data have the potential to provide a new perspective on the evolution of margins in the Continent-Ocean Transition zone.

Poulaki E. et al. (2025) - Granitic intrusions facilitate rapid mantle exhumation along an oceanic detachment fault. Under Review in Nature Communications.

Sanfilippo, et al. (2025) - Heterogeneous Earth's mantle drilled at an embryonic ocean. Nature Communications, 16(1), https://doi.org/10.1038/s41467-025-57121-0.

Zitellini N. et al. (2025) - Proceedings of the International Ocean Discovery Program Volume 402, publications.iodp.org, https://doi.org/10.14379/iodp.proc.402.101.2025.

Empirical scaling relationships between fault length and displacement-rates modulated by fault interactions in extensional regimes

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Keywords: scaling selationships, throw-rate vs. fault length, fault interaction.

The slip-rates of faults are expected to scale with the fault lengths because the geometric moment for a fault is related to its dimensions. However, significant scatter exists in datasets for this relationship, and lack of understanding of why the scatter exists hinders our ability to use it for seismic hazard purposes and to understand continental deformation. We present throw-rate versus fault length datasets for three areas of extension in Italy which exhibit progressively more faults across strike. We show that the scatter in the slip-rate versus length data for the three areas increases with a greater number of faults across strike and hence greater across strike fault interaction. We discuss these results in terms of seismic hazard assessment and continental deformation.

Finally, we highlight that the structural geology and the earthquake geology knowledge from this study are driving the identification of crucial locations along the Calabrian forearc for a new INGV-led project within the framework of the National Hydrogeochemical Network. In particular, locations nearby seismically-active normal faults are being identified to install multiparametric stations measuring in continuous chemical and physical parameters, with the aim to better understand correlations between seismically active normal faults and crustal and deep fluid migrations. This will allow us to better define the geodynamic processes occurring in one of the most tectonically-active regions within the Mediterranean realm.

Whiteschists in the Adula nappe – New discovery and potential implications for the interpretation of pressure variations

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Keywords: whiteschists, high pressure, shear zones.

We present first results from newly discovered whiteschists in the Central Alps (Adula nappe). Whiteschists were found as veins cross-cutting eclogite lenses, which in turn are embedded in a thick pile of alternating metaragranitoids and micaschists. Veins developed after brittle fracturing which provided the fluid pathways. The whitescists geochemical patterns suggest that fluids originated within the eclogite lens, without input from exotic sources. Whiteschists show a peak assemblage consisting of garnet + talc + kyanite + chloritoid + rutile, locally substituted by a retrograde assemblage of phlogopite and pargasite. Quartz is extremely rare. Garnet composition is highly variable from almandine-rich cores to unusually high content of pyrope in large rims (up to 70%). Garnet cores encompass abundant inclusions, among the other of blue and green amphibole and clinopyroxene. Rims contain instead only inclusions of rutile and talc. Preliminary P-T estimations point toward a significant P increase occurred during garnet growth, from HP to UHP conditions. These findings represent a unicum in the regional tectono-metamorphic pattern, raising fundamental questions about the processes that control the dynamic and heterogeneous pressure distribution throughout reacting and deforming fluid-rock interface volumes. Field and petrological investigations are combined with visco-frictional numerical modelling of fluids stresses along shear zones to provide potential explanation of the apparent discrepancies between the regional tectonic settings and petrologically-inferred pressure-temperature-depth paths.

Post-collisional evolution in extensional tectonic regime: Insights from numerical models

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Keywords: rifting, numerical models, structures inheritance.

The Wilson Cycle encapsulates the periodic opening and closing of ocean basins, playing a fundamental role in Earth's tectonic evolution (e.g., Wilson et al., 2019). Although ocean formation starting from a homogeneous crust and subduction processes have been largely studied by means of analogous and numerical models (e.g. Zwaan et al., 2016; Erdős et al., 2019), the transitional phase between the end of continental collision and the onset of extension leading to continental break-up remains poorly analysed.

In this work, we use the 2D thermo-mechanical code FALCON (Regorda et al., 2023) to explore the evolution of convergent–divergent settings characterised by an initial phase of oceanic subduction leading to continental collision and a successive phase of the extensional regime. In particular, we focus our analysis on the post-orogenic phase, investigating if and how different boundary conditions on the velocity could affect the onset and the evolution of the rifting in correspondence of a post-collisional thickened continental crust.

Our simulations show that post-collisional extension is strongly influenced by structural inheritance from the preceding subduction–collision stages. In fact, high strain rates localize along the former subduction channel, while shallower crustal levels accommodate deformation through the reactivation of pre-existing thrusts as normal faults. The extension phase promotes progressive thinning of the post-collisional thickened crust, facilitated by asthenospheric upwelling and thermal weakening at the base of the subducting plate. This process leads to strain localization and the development of an extensional tectonic regime, characterized by normal fault systems and associated topographic subsidence.

Erdős Z. et al. (2019) - Control of increased sedimentation on orogenic fold-and-thrust belt structure - insights into the evolution of the western alps. Solid Earth, 10(2), 391-404, https://doi.org.10.5194/se-10-391-2019.

Regorda A. et al. (2023) - Rifting venus: Insights from numerical modeling. Journal of Geophysical Research: Planets, 128(3), e2022JE007588, https://doi.org.10.1029/2022JE007588.

Wilson R.W. et al. (2019) - Fifty years of the wilson cycle concept in plate tectonics: an overview. Geological Society, London, Special Publications, 470(1), 1-17, https://doi.org.10.1144/SP470-2019-58.

Zwaan F. et al. (2016) - Insights into the effects of oblique extension on continental rift interaction from 3d analogue and numerical models. Tectonophysics, 693, 239-260, https://doi.org.10.1016/j.tecto.2016.02.036.

Analysing the post-collisional evolution of the Variscan chain in the Valpelline Series (Austroalpine domain of the Western Alps)

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Keywords: Adria plate lithosphere, Permian evolution, post-collisional extension.

In the Wilson Cycle, the post-collisional phase marks a crucial transition from a convergent to a divergent tectonic regime. This stage is often characterized by orogenic collapse, a process driven by volumetric forces that act to restore isostatic balance within the orogen. Such collapse can lead to crustal extension, thermal anomalies, and mechanical weakening, and has traditionally been viewed as the primary driver of post-collisional extension and its effects potentially continuing long after convergence has ceased. However, recent investigations of the post-Variscan convergence in the pre-Alpine basement of the Alps reveal a more complex picture. These studies document high- to ultrahigh-temperature (HT to UHT) conditions in the deep crust, along with lower Permian mantle-derived mafic magmatism. These features are difficult to reconcile with a prolonged orogenic collapse following the Variscan convergence (Roda et al., 2023). To better understand the post-collisional evolution of the Variscan belt within the future Adria plate, we compare 2D thermomechanical models using the numerical code FALCON (Regorda et al., 2023) with the pressure–temperature–time (P–T–t) evolution of rocks from the Permian basement of Adria. We simulate an oceanic subduction over 20 Myr leading to continental collision followed by three post-collisional scenarios lasting up to 35 Myr (335–280 Ma): (i) a purely gravitational collapse phase lasting 5 Myr followed by extension, (ii) a progressively increasing extension rate during 5 Myr followed by constant extension, and (iii) a scenario with immediate constant extension rate. In all cases the half-spreading extension rate is fixed to 0.2 cm/yr. The modelled thermomechanical evolutions are compared with the P–T–t paths of rocks from the Valpelline Series, which record two distinct post-collisional exhumation stages in the Early Permian. These stages, characterized by differing P–T conditions (Caso et al., 2024), have been dated using high-precision zircon geochronology. Among the three scenarios, the model (iii) with a constant extension rate best reproduces the metamorphic evolution of the Valpelline rocks. This model also aligns with the P–T evolution proposed for the Ivrea-Verbano Zone by multiple authors. Additionally, it predicts a gradual reduction in topography, resulting in the development of topographic basins consistent with interpretations for the origin of early Permian basins in the Southern Alps. These findings suggest that a divergent tectonic setting began shortly after continental collision. A single phase of gravitational collapse alone cannot account for the observed P–T conditions recorded during metamorphism. This highlights the need to reconsider the tectonic framework of the Late Carboniferous-Early Permian, challenging the traditional emphasis on gravitational collapse as the dominant post-collisional process in the classic Wilson Cycle model.

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Regorda A. et al. (2023) - Rifting venus: Insights from numerical modeling. Journal of Geophysical Research: Planets, 128(3), e2022JE007588, https://doi.org/10.1029/2022JE007588.

Roda M. et al. (2023) - Metamorphic Remnants of the Variscan Orogeny across the Alps and Their Tectonic Significance. Geosciences, 10(13), 300, https://doi.org/10.3390/geosciences13100300.

Witnesses of an early Miocene Markan arc volcanism: shale-related minibasins of the Karvandar Basin (South Sistan, SE Iran)

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Keywords: sedimentary provenance, magnetostratigraphy, mud volcanism.

Sedimentary deposits in foreland basins offer valuable information about the geological development of their adjacent highlands. Situated in the outer foreland of the South Sistan Suture Zone (southeastern Iran), the Karvandar Basin contains a several-kilometer-thick succession of shallow marine to continental clastic sediments arranged in elongated, sub-circular synclines. These synclines rest atop a mud-rich formation that includes exotic volcanic blocks and hosts one of Iran's largest mud volcanoes - the Pirgel mud volcano.

In this study, we present a ~3.5 km thick magnetostratigraphic section, complemented by U-Pb zircon dating of interbedded tuff layers, which constrains the age of sedimentation in the Karvandar Basin to approximately 24-17 million years ago. Analysis of sandstone and microconglomerate composition, along with paleocurrent data, indicates a primary volcanic arc source located northeast of the basin. We interpret the underlying mud-rich unit containing volcanic blocks as an olistostrome, likely derived from the same source as the overlying clastic sediments. U-Pb dating of calcite from a coral fragment within the olistostrome yields an age of ~24.5 Ma.

The lack of large-scale anticlines and the presence of angular unconformities suggest that the sub-circular synclines formed through gravity-driven downbuilding into the unconsolidated, fluid-saturated olistostrome-similar to the formation of salt-related minibasins. Our integrated results point to a late Oligocene to early Miocene volcanic arc in the Makran region as the source of the clastic sediments. This finding pushes back the timing of arc volcanism associated with the Makran subduction zone by roughly 5 million years, predating the previously known onset from the Mirabad pluton (~19 Ma), located northeast of the Karvandar Basin.

New insights into the Gela mass-transport complex (Sicily Channel) from 3D seismic reflection data

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Keywords: Gela foredeep basin, submarine landslides, 3D seismic.

The Gela basin, located offshore southern Sicily, is a Plio-Quaternary foredeep formed at the frontal margin of the Maghrebian fold-and-thrust belt. The basin is filled by up to 2.5 km of marine sediments overlying the Gela nappe, a tectonic mélange emplaced during the early Pleistocene.

One of the most prominent features within the basin is the Gela submarine slide, a large mass-transport complex (MTC) extending over an area of ca. 1,500 km^2. Studies dating back to the early 1990 originally interpreted the Gela slide as a single, laterally continuous, slide slab mobilized along a basin-wide detachment surface (Trincardi and Argnani, 1990). This interpretation, based on sparse 2D seismic reflection data, emphasized the role of a weak basal horizon in driving sediment deformation and the influence of nappe-related tectonic relief in triggering the event.

Recent analysis of high-resolution 3D seismic reflection data reveal that the slide body, rather than being composed of remobilized slope sediments, comprises multiple reworked units. These include older, pre-existing slump bodies and debris flows that have been reactivated, incorporated into the larger slide complex, and further deformed. Seismic facies within the Gela MTC are highly heterogeneous, showing a mixture of coherent slide blocks, rotated and tilted strata, chaotic units, and discontinuous reflectors indicative of multiple deformation phases. The presence of lateral ramps, thrust-related imbrications and pop up structures at the toe region, and variable basal detachment geometries suggests a more complex kinematic evolution, likely involving retrogressive failures and basin-constrained deformation patterns.

These observations suggest that the Gela slide is not a single-stage event, but rather the result of multi-phase slope instability that culminated in a large MTC, likely influenced by the underlying tectonic architecture and regional uplift. The 3D seismic interpretation provides a further level of detail, significantly improving our understanding of the dynamics and evolution of submarine mass movements in foredeep settings.

Trincardi F. & Argnani A. (1990) - Gela submarine slide: A major basin-wide event in the Plio-Quaternary foredeep of Sicily. Geo-Marine Letters, 10, 13-21.

Middle Pleistocene Differential Uplift of Sedimentary Basins in the Southern Central Anatolian Plateau: Insights from the Mut and Manavgat Basins

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Keywords: biostratigraphy, Eastern Mediterranean, Middle Pleistocene uplift.

The southern margin of the Central Anatolian Plateau (CAP) has experienced rapid, multi-phase uplift during the Quaternary, driven by deep lithospheric processes such as slab break-off, delamination, and crustal thickening. This margin represents a zone of significant geodynamic activity, and understanding its uplift history is essential for reconstructing the plateau's evolution and the broader geodynamics of the Eastern Mediterranean. In this study, we present new stratigraphic and micropaleontological data from the Manavgat Basin to constrain the timing and rate of uplift. We focus on a 65 m thick composite fan-delta succession (MNV-4) of the Karpuzçay Formation, currently exposed at 150 m a.s.l. This marine littoral delta system comprises mouth bar, delta front, and prodelta deposits, reflecting fluctuating conditions from shallow to open marine environments influenced by tectonic activity and sea-level changes during the Quaternary. The succession is characterized by rhythmic alternations of marl, silty marl, fine to coarse sands, and intercalated conglomeratic horizons and slump deposits. Marly layers, interpreted as prodelta facies, were sampled for micropaleontological analysis. No ostracods were recovered, likely reflecting a high-energy, dynamic deltaic setting. Foraminiferal analysis revealed the presence of *Globigerinoides ruber* (pink) since the basal samples, while calcareous nannofossil data indicate the First Occurrence (FO) of *Emiliania huxleyi* (0.26 Ma) near the base. Both markers place the section in the late Middle Pleistocene, the youngest documented marine deposition age in the Manavgat Basin. These results yield an estimated uplift rate of ~1 m/kyr. For comparison, previous work by Sari et al. (2025) documented a 71 m thick marine succession (Tol-1 section) in the Mut Basin at 1171 m a.s.l., reaching an age of 211 ka at the top, and indicating an uplift rate of ~5.9 m/kyr. Despite similar ages, the two basins differ markedly in elevation, suggesting significant differential uplift within the southern CAP during the late Middle Pleistocene. We interpret these differences as a result of localized geodynamic processes: the Mut Basin likely reflects stronger asthenospheric upwelling and lithospheric removal following slab break-off, whereas the Manavgat Basin records more subdued extension-driven uplift.

Sari S. et al. (2025) - The Middle Pleistocene uplift of the Central Anatolian Plateau (CAP) southern margin: New evidence from the Mut Basin (South Turkey). EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-10350, https://doi.org/10.5194/egusphere-egu25-10350.

Rheological heterogeneities and strain localization in the exhumed mantle of an Embryonic Ocean Basin

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Keywords: ocean drilling, Tyrrhenian Sea, fault.

Drilling at the Tyrrhenian Sea ocean-continent transition during IODP Expedition 402 recovered a heterogeneous mantle section (Sanfilippo et al., 2025) revealing the interplay between lithology and deformation during the initial stages of oceanization. The cores contain variably serpentinized peridotites, pyroxenites, mafic intrusions, and mylonitic to protomylonitic granitic bodies, reflecting a complex lithological mosaic. Structural and microstructural analyses show deformation localized preferentially along weaker lithologies: mylonitic fabrics and dynamic recrystallization are concentrated in mafic and felsic intrusions, while adjacent peridotites preserve porphyroclastic textures or evolve into peridotite mylonites near magmatic contacts. Clinopyroxene- and plagioclase-rich veins within lherzolites mark zones of melt percolation coupled to deformation. Zircon and apatite U-Pb geochronologic analyses from the granitic intrusions yield crystallization ages of ~4 Ma (Poulaki et al., 2025). Coupled with ages of the overlaying sediments, these data suggest rapid exhumation within ~0.5 Myr. The association of strain localization with felsic and mafic intrusions, as well as within inherited mantle peridotites suggests that lithological heterogeneity controlled the nucleation and persistence of detachment faulting, enabling efficient mantle exhumation without the development of an igneous crust. These results emphasize the fundamental role of compositional and rheological contrasts in focusing deformation at magma-poor rifted margins.

Poulaki E. et al. (2025) - Rapid exhumation of mantle rocks along detachment faults facilitated by felsic granitoid intrusions at a continent-ocean transition drilled in the Tyrrhenian Sea, EGU General Assembly 2025: Vienna, Austria.

Sanfilippo A. et al. (2025) - Heterogeneous Earth's mantle drilled at an embryonic ocean. Nature Communications, 16, 2016.

Database of Italian Pressures (DIPs): first Italian database of subsurface pressures from well information

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Keywords: pore pressures, seismotectonics, exploration wells.

We present DIPs, the first Database of Italian Pressures, which collects subsurface pressure data acquired from exploration oil and gas wells (Vitagliano et al., 2025). DIPs aims to promote collaboration and advancements in research within both national and international scientific communities by enhancing access to information on pore pressures, and, when available, lithostatic and leak off pressures. Mapping subsurface pore pressure is critical in various geological disciplines related to petroleum resources, geothermal energy, geohazard assessment, groundwater management, and geotechnical engineering (e.g., Zoback & Byerlee, 1975; Birkholzer et al., 2015; Ganguli & Sen, 2020). For instance, quantifying pore pressure is crucial for evaluating the effective stress of rocks and assessing fault reactivation. Regarding migration and entrapment of fluids, it is also essential for ensuring the integrity of cap rock and long-term containment. In addition, understanding subsurface conditions aids in the safe and efficient extraction of natural resources, also helping to prevent blowouts, kicks, and borehole collapses.

DIPs provides pressure trends derived from original documentation concerning expired mining titles deposited since 1957 at UNMIG, the National Mining Office for Hydrocarbons and Georesources, which falls under the Ministry of Environment and Energy Security (www.videpi.com). Before publication on DIPS, the original information undergoes a reliability check and calculation process. The obtained pressure values are presented in graphical formats (e.g., pressure-depth plots) and can be downloaded as text files by clicking on individual wells. Each borehole output includes information about the data source and the methodology used to calculate the pressure trends. Specifically, pore pressures are derived from direct and indirect measurements. Direct measurements are obtained during formation or production tests and relate to specific stratigraphic intervals within the well. Indirect measurements are calculated based on specific parameters, such as the weight of drilling mud or geophysical log data, and are distributed throughout the vertical profile of the well. Furthermore, rock fracturing pressures are available for selected wells and, when such information exists, is sourced from leak-off tests, thus pertaining to specific stratigraphic intervals. In some cases, if additional information is available, the fracturing gradient along the vertical profile of the well is also displayed. Lithostatic pressures are attributed using average bulk density values derived from literature or calculated using geophysical logs.

Finally, we present several recent studies conducted in Italy to illustrate how pressure analysis can be developed and integrated with various geoscience disciplines, including seismotectonics, geochemistry, and hydrogeology.

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Ganguli S.S. & Sen S. (2020) - Investigation of present-day in-situ stresses and pore pressure in the south Cambay Basin, western India: implications for drilling, reservoir development and fault reactivation. Mar. Petrol. Geol., 118, 104422, https://doi.org/10.1016/j.marpetgeo.2020.104422.

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Zoback M.D. & Byerlee J.D. (1975) - Permeability and Effective Stress. AAPG Bulletin, 59 (1), 154-158, https://doi.org/10.1306/83D91C40-16C7-11D7-8645000102C1865D.

An experimental study of the growth of segmented normal faults

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Keywords: fault segmentation, interferometric technique, rock analogue material.

Normal faults are thought to grow through an initial phase of rapid propagation of segments, followed by a phase of slip accumulation and segment interaction and linkage. This model for fault growth is largely indirectly derived from observing finite strain fault structures at different stages of evolution within seismic reflection and field data. In this work, we aim to test this growth model through laboratory experiments on rock analogue material, detailing the progression of both the processes of fault segment propagation and displacement accommodation. We selected a composite rock analogue material made of a precise mix of sand, cement, kaolin, and water, which provides a cohesive and diffusive material. The experiments are performed using a biaxial apparatus where the compression platform speed can be as low as 0.1µm/s. Deformation behaviour is recorded continuously by means of an interferometric technique called the Diffusive Wave Spectroscopy (DWS) method. The apparatus is highly sensitive both spatially and temporally, allowing us to measure deformation over very small time increments of 17 to 50 milliseconds fixed by the frame rate of the camera, and record displacements of the order of a fraction of micrometres. This unique setup allows us to study in a high level of detail the processes of fault growth. Given that faults are important avenues for fluid migration, this study can have important implications for underground gas storage and hydrocarbon industries. Moreover, slip along faults triggers earthquakes; thus, quantifying the fault growth is key to mitigating associated hazards.

S9.

Faults, fluids, and fractures: bridging structural, mechanical and geochemical perspectives

Conveners and Chairpersons

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Understanding the role of local stress states on permeability anisotropy computed after DFN modelling of low porosity fractured and faulted limestone: the case study of the Viggiano Mt., southern Apennines (Italy)

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Keywords: permeability anisotropy, stress-modulated flow, Discrete Fracture Network (DFN) modeling.

Assessing the influence of local stress states on the permeability of fractured rock volumes is critical for accurately predicting fluid flow in the subsurface (Zoback et al., 1992). While the literature largely emphasizes the impact of stress on 2D fracture networks - either theoretical or derived from idealized experiments (Song et al., 2024), to our knowledge, field-based results on 3D fracture networks in carbonate rocks are lacking. To address this gap, we investigate Mesozoic limestones cropping out along the flanks of the Agri Valley Basin, which experienced Miocene contractional tectonics followed by Plio-Quaternary transtensional deformation (Manniello et al., 2024). Outcrops were chosen away from major transtensional faults to analyse the geometry and dimensional properties of fracture systems, encompassing multiple fracture sets. We performed Discrete Fracture Network (DFN) modelling on 5 m-sided geocellular volumes, representing four distinct carbonate units:

- *Scarrone La Macchia II (SLM II)* – Sinemurian–Pliensbachian well-layered wackestones–grainstones from a low-energy lagoon;
- *Scarrone La Macchia I (SLM I)* – Toarcian oolitic carbonates from a ramp setting with amalgamated beds;
- *Piana del Buon Cuore (PBC)* – Upper Jurassic–Lower Cretaceous oolitic and oncolitic limestones from a high-energy platform margin;
- *Il Monte (ILM)* – massive Cretaceous rudstones and grainstones deposited along a paleo-slope.

Using *dfnWorks*®, we simulated fracture networks under burial conditions at 500 m depth, representative of the base of the local fractured and karstified carbonate aquifer. Principal stress values were constrained from the literature: $\sigma v \approx 13$ MPa, $\sigma hmax \approx 10$ MPa (NW–SE), and $\sigma hmin \approx 7.6$ MPa (NE–SW). Stress-modulated theoretical fracture apertures were used to compute effective horizontal permeability (*keff*), and Lagrangian solute transport simulations were employed to track flow paths and breakthrough times. Relative to unstressed DFN conditions (Abdallah et al., 2024), the results reveal contrasting *keff* responses across units. In SLM I, stress conditions amplify horizontal permeability anisotropy, promoting channelized flow, increased path tortuosity, and delayed breakthrough. PBC and ILM exhibit similar but less pronounced trends. In contrast, SLM II shows reduced anisotropy at 500 m depth, likely due to its distinct fracture network geometry. Ongoing work integrates microstructural and mineralogical analyses to incorporate true aperture data into our permeability estimates.

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Internal structure, petrophysical properties, and fluid flow behavior of normal fault zones in the low-porosity carbonates of peninsular Italy

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Keywords: faulting processes, structural diagenesis, fault permeability.

Over the years, carbonate fault zones have been widely studied to assess the deformation mechanisms and diagenetic processes associated to a variety of tectonic regimes, burial depths, and rock lithologies (Agosta & Tondi, 2010). In this framework, normal faults crosscutting low-porosity carbonates and exposed along the axial zone of the central and southern Apennines have been investigated to document their internal structure, petrophysical properties and fluid flow behavior. The results have been employed to better decipher the time-space evolution of mineralization and fluid pathways within carbonates exploited for geothermal energy production, secure storage of nuclear waste in the subsurface, CO_2 confinement at depth, and groundwater management. In the latter years, the studies have focused on the possible entrapment of deep-seated fluids along carbonate-hosted normal faults of the Apennines, and associated transients of high pore pressure during seismic faulting (Curzi et al., 2024). This presentation combines the results of both field and microscale structural analyses with those after mineralogical, petrophysical, rock physical, and geochemical investigations of carbonate samples collected along major normal faults dissecting the Apenninic carbonate platform. The norml faults crosscut Mesozoic limestones or dolostones, the fault rocks are made up of both grain- and matrix-supported carbonate cataclasites. Within limestones, the most comminuted, matrix-supported fault rocks close to the main slip surfaces were cemented by meteoric-derived fluids mixed with formation waters. Conversely, fault rocks in dolostones do not show any significant fault-related mineralization. In terms of their petrophysical and rock physical properties, both limestone and dolostone fault rocks are characterized by a pore geometry that varies as function of the rock texture. Both porosity, Φ, and permeability, k, increase in the vicinity of the main slip surfaces. Differently, the cemented fault rocks in limestones exhibit very low values of both Φ and k, similar to those characterizing the limestone host rocks (Ferraro et al., 2020). These cemented fault rocks therefore form local baffles inhibiting the cross-fault fluid flow. Within carbonate fault damage zones, crosscut by fault-related fractures and smaller scale faults, data are consistent with a decay of fracture intensity with distance from the main slip surfaces (Volatili et al., 2022). Such a decay is represented by power-law functions in which a main, broader decay associated to the largest slip surfaces is modulated to more localized decays due to the smaller faults. The experimental data are interpreted so that the fault rocks are modelled by applying the Kozeny-Carman Φ-k, whereas the fractured matrices by employing the Budianski-O'Connell Φ-k correlation.

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Geology and water level of the Pilato Lake in the Sibillini Mountains (Northern Apennine)

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Keywords: Pilato Lake, water level, hydrogeology.

Pilato Lake, located at an altitude of 1950 m, is positioned within the Sibillini Mountains National Park, in the Umbria-Marche Apennines. It is nestled within a glaciated valley (Damiani, 1975) below Mount Vettore, the highest peak of Sibillini Mountains. Pilato Lake is well known for being the home of the endemic species Chirocephalus marchesonii. This characteristic has made the lake an important object of study from a biological point of view. Geological knowledge remains scarce, but interest has increased following the 2016-2017 Central Italy seismic sequence. The numerous coseismic ground ruptures may have generated new fracture systems and opened the question of water loss from the lake. The Pilato Lake valley is characterised exclusively by Jurassic calcareous formations of high structural Calcare Massiccio and Corniola, the latter of which is affected by a network of Jurassic normal faults that pass under the lake. However, the lake does not rest directly on the limestones but on recent slope and glacial deposits, which act as aquitards. During recent summers, Pilato Lake has undergone repeated total drying up, the leading cause of which seems to be past meteorological conditions (Martarelli et al., 2019). It is also plausible to think of a geological influence linked to forming coseismic ruptures under the lake (Martarelli et al., 2022), but interferometric images seem to deny this hypothesis. The lake level does not appear to be influenced by the slope debris, coming mainly from the valley's eastern side, given the absence of substantial variations in the last hundred years. Thanks to a detailed photogrammetric survey, the potential maximum volume of Pilato Lake is estimated to be more than 100.000 m^3, with an exponential variation in the volume of water. A geophysical survey allowed for the detailed examination of the debris levels on which the lake rests, in terms of internal structure, thickness and especially permeability.

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Seismic cycle-controlled hydrocarbon vertical migration in the Ragusa Oil Field (SE Sicily-southern Italy): evidence from field and microstructural analysis

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Keywords: hydrocarbon seepage, fault/fracture, stress cycling.

Hydrocarbon seepage at the Earth's surface provides crucial insights into subsurface petroleum systems, especially in tectonically active settings. This study investigates the relationship between fault-controlled deformation and vertical hydrocarbon migration in the Ragusa Oil Field (south-eastern Sicily), a long-exploited petroleum district within the Hyblean foreland. Through integrated field surveys, microstructural analyses, and Discrete Fracture Network (DFN) modelling, we examine how stress cycling during the seismic cycle may influences fracture reactivation and hydrocarbon ascent from deep carbonate reservoirs. Evidence from abandoned asphalt mines and active seep sites reveals both stratigraphic layer impregnation and focused fault/fracture-controlled oil pathways, particularly along NE-SW trending extensional structures linked to foreland bulging dynamics and along the NNW-SSE Scicli–Ragusa Fault System, a major strike-slip fault zone intersecting the Ragusa carbonate platform. Structural and stratigraphic data from abandoned asphalt mines and surface outcrops reveal at first that hydrocarbon migration is facilitated by both fault intersection and fault-controlled permeability enhancements. Microscale structural analysis on sampled fault breccia revealed channelized structures, injection features, and clast-cortex grains, all suggesting the occurrence of transient and localized pulses of pressurized hydrocarbons during coseismic slip. Radiometric dating of bitumen-bearing alluvial sediments and recent oil spills following a seismic sequence in the area supports a model of cyclic fluid mobilization modulated by static stress perturbations in the crust. Considering fault rupture kinematics in the area, our findings highlight the roles of interseismic compression and post-seismic dilatancy in opening migration pathways. These preliminary findings underscore the roles of fault/fracture reactivation and seismic strain in governing fluid mobility in carbonate reservoirs, with implications for petroleum exploration and geohazard assessment in seismically active forelands.

Hydrothermal silicification and extensional faulting: insights from combined structural, geochemical and petrophysical analyses (Lemnos Island, Greece)

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Keywords: normal fault, silicification, petrophysical properties.

In upper crustal fault zones, silica-bearing hydrothermal fluids may affect petrophysical and mechanical properties of rocks by modifying their texture and mineralogy with strong implications on geofluid storage and flow potential. However, in the subsurface, it is extremely difficult to predict the geometry of silicified rock volumes along and around fault zones as well as their petrophysical properties and, therefore, well exposed outcrop analogues can provide important insights. The Kornos-Aghios Ioannis Fault (KAIF) on Lemnos Island (Greece) is a silicified extensional fault system active at shallow depth (< 1 km), that juxtaposes volcanic rocks against turbidite sandstones. In this study, we investigate the source and temperature of mineralizing fluids as well as the mineralogy and petrophysics of silicified rocks, including massively silicified sandstones and fault core rocks (i.e. breccias, cataclasites, ultracataclasites).

Fluid inclusion microthermometry and stable isotope analyses of hydrothermal minerals suggest silica precipitation by acid-sulfate hydrothermal fluids having average temperatures of 160-170 °C and a remarkable meteoric signature. Due to this fault-controlled silicification process, the permeability of silicified fault cores and damage zones is 1-3 orders of magnitude lower than pristine host rock. In this silicified volume characterized by degraded petrphysical properties (100's of meters wide), the permeability drop produced by silica precipitation is partially counterbalanced by higher fracture density and connectivity.

In this context, our results also show that the extension and the intensity of hydrothermal silicification is heterogeneous along-fault strike, producing an along-strike variability in the permeability structure of hydrothermally silicified faults.

Modelling faulting in the brittle crust with the Particle Finite Element Method (P-FEM)

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Keywords: faults, numerical modelling, elastoplastic.

Accurately modeling faulting in the brittle crust remains a challenge due to limitations in numerical algorithms and problems in choosing realistic constitutive models. These challenges are reflected in difficulties linking observations across scales: from laboratory to outcrop and up to regional geology.

Here we present the Geotechnical Particle Finite Element Method (P-FEM), a large-deformation numerical tool developed to capture detailed progressive failure and fracturing using a non-local formulation.

A key advantage of P-FEM is its ability to simulate localized shear bands (fault zones with finite thickness) that naturally emerge independent of mesh discretization, both in thickness and orientation. Continuous remeshing further enables the modeling of large deformations within a Lagrangian framework, and techniques used to minimize numerical diffusion help producing realistic localized shear/fault zone patterns. Additionally, P-FEM benefits from its foundation in standard finite elements, allowing to use efficient and accurate solvers (tested through years by a large community of users) and a wide library of constitutive models to simulate various geo-materials.

The elastoplastic constitutive models can be finely calibrated to include complex non-linear effects, including strain weakening and softening, poroelastic effects, and strength envelopes with a cap (i.e. porosity collapse in compression). This results in very realistic simulations of a large class of materials, including non- or weakly-cohesive fault gouges, weak porous rocks (that could develop deformation/compaction bands), and "standard" brittle-frictional-plastic materials. Multiphysics implementations including fluid and heat flow are also available but will not be specifically discussed here.

These capabilities make P-FEM particularly suited for investigating fundamental tectonic processes such as (i) fault nucleation and growth in mechanically layered materials, (ii) the interplay between faulting and folding in thrust belts, and (iii) the development of fault damage and/or process zones in materials with heterogeneous mechanical properties. Our contribution will outline the P-FEM method and discuss its application to these tectonic problems.

Statistical Assessment of Fracture Areal Intensity (P21) Representative Elementary Area in Digital Outcrop Models

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Keywords: P21, REA, stochastic DFN.

Among the geometrical parameters that can be calculated from an outcrop analogue, fracture areal intensity (P21), defined as the ratio between the total sum of fracture trace length and the sampling area, represents the stopping criterion of 2D stochastic Discrete Fracture Network models (DFN) or 3D simulations if properly upscaled to its volumetric equivalent (P32). Given the heterogeneous nature of fractured rock masses, P21 calculation is inherently scale and position dependent, meaning that its value changes depending on the scan area size and its position within the outcrop boundary. For this reason, P21 calculation cannot be separated from the concept of Representative Elementary Volume (REV) or Area (REA), in case of 2D outcrop studies (Bear, 1975). Depending on the field of application, REV or REA size definition changes, adapting to the different sampling strategies and parameters specific to that research field (Sari, 2021). In the case of fractured outcrops, it is not uncommon that the upper boundary of the scan area size range, over which the P21 variable is calculated closely matches the outcrop size, configuring the possibility of reducing the sampling outcomes to few, almost identical values, resulting in unmeaningful data. In this contribution we present a two-step methodology to quantitatively assess P21 REA of digitalized fracture networks from TS-DOMs (Textured Surface Digital Outcrop Models). The first step consist in the analysis of the spatial distribution of fractures, to check if they are homogeneously distributed across the outcrop (Bistacchi et al., 2020). This step is fundamental to avoid including systematically denser zones in the analysis, that would introduce a bias in the P21 variance. These areas, if any, will be considered separately. The second step includes the P21 data collection and a series of chained hypotheses tests to check all the necessary underlying assumptions (normality, homogeneity of variances) to finally perform the ANOVA test (Mooi et al., 2018) to compare the different groups of P21 data and therefore assess stationarity from a certain scan area size onward. Data are collected with scan areas of increasing size, randomly distributed across the outcrop to maintain the independence hypothesis. Results will show the presence/absence of a P21 REA and will highlight the scan area size upper limit beyond which collecting P21 values become meaningless. In the end, the presence of trends in the spatial distribution of P21 values at the REA size will be inspected to find useful relationships to distribute P21 values in reservoir-scale DFNs.

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Fast, fluid-mediated transition from dynamic rupturing to aseismic slip at the base of the seismogenic continental crust

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Keywords: fluid-rock interaction, seismicity, weakening.

Chemo-mechanical interactions between fluids and rocks play a fundamental role in governing the transition from frictional to viscous deformation, as well as the interplay between seismic and aseismic slip in the continental crust. In this study, we quantify the timing and extent of weakening processes driven by fluid-rock interaction, and their impact on slip behavior within seismogenic fault zones. Through an integrated approach combining field observations, microstructural characterization, and micromechanical modeling, we investigate the evolution of phyllosilicate- and carbonate-rich brittle-ductile shear zones within the Rieserferner granitoid pluton (Eastern Alps).

Here, transient overpressure of (H_2O + CO_2)-bearing fluids facilitated dynamic rupture in a mechanically strong host rock (> 100 MPa), while promoting progressive weakening via feldspar-to-mica alteration reactions that led to the formation of low-strength phyllonites. These fault rocks deformed primarily by frictional-viscous flow under near-lithostatic fluid pressure and low differential stress conditions (< 10 MPa). Overprinted networks of microscale veins document episodic brittle failure events linked to transient increases in creep rates (up to 10^{-7} s^{-1}) occurring over timescales of days to months, consistent with the slip velocities expected for slow earthquakes (~10^{-8} m/s).

Our results place new constraints on how fluid composition and pressure conditions influence fault rheology and the evolution of seismogenic behavior in phyllosilicate-rich fault zones. Weakening can take place over relatively short timescales (months to years), comparable to the interseismic period, enabling a transition from dynamic rupture to sustained viscous creep. The combination of intense strain localization, low permeability of phyllonitic cores, and progressive fluid evolution—particularly CO_2 enrichment—may contribute to episodic brittle instabilities during phases of accelerated creep. This chemo-mechanical transformation ultimately governs the potential for slow slip and transient seismic events along faults that would otherwise deform aseismically.

Laboratory earthquakes under hydrothermal conditions in Neapolitan Yellow Tuff (Campi Flegrei, Italy)

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Keywords: friction, hydrothermal, earthquakes.

In recent decades, the Campi Flegrei volcanic caldera in Italy has experienced significant ground uplift, ranging from decimetres to meters annually, alongside shallow seismic activity with magnitudes reaching Md 4.6 (Danesi et al., 2024; Patanè et al., 2025). Despite being one of the most closely monitored volcanic regions, the mechanical properties of its fault systems under hydrothermal conditions and their impact on the seismic cycle remain largely unexplored. This study examines the frictional properties of simulated faults composed of Neapolitan Yellow Tuff, which represents the shallow seismogenic volume of Campi Flegrei. Utilizing a specialized rotary shear apparatus (RoSA) with a hydrothermal vessel (HYDROS), the research adopts a multivariant experimental approach, by changing the effective normal stress (σneff from 5 to 30 MPa), temperature (T from 23 to 400 °C), and fluid pressure (Pf at 5 and 30 MPa). These variables enable to investigate the interactions between liquid, vapor, and supercritical water throughout the simulated seismic cycles. Results indicate that both temperature and fluid pressure influence the friction coefficient, which ranges from 0.55 at 23 °C and Pf = 5 MPa to 0.80 at 300 °C and Pf = 30 MPa. Stable sliding occurs at 23 °C and σneff ≤ 20 MPa, while laboratory earthquakes (unstable sliding) are observed at temperatures of 150 °C and above. Stress drops during these laboratory earthquakes increase with temperature and σneff, with total stress drops of up to 28 MPa recorded at higher temperatures. X ray powder diffraction (XRPD) and Fourier transform infrared spectroscopy (FTIR) reveal significant dehydration of the tuff under unstable conditions, in agreement with X-ray fluorescence (XRF), in relation to the breakdown of original zeolite minerals such as chabazite and phillipsite. Scanning electron microscopy (BSE-SEM) provides evidence of morphological smoothing of the mineral grains and the dominance of feldspars in the dehydrated charges. BSEM-SEM shows that large stress drops correlate with fault gouge cementation from pressure-solution and sintering during inter-seismic phases, as well as gouge frictional melting during co-seismic phases. Data from deep wells (2-3 km) indicate that the experimental conditions mirror those at depths of ≤ 2 km within the caldera, where low-magnitude earthquakes have been documented since 2000 (Piochi et al., 2014; Tramelli et al., 2022). Overall, the mechanical, chemical, and microstructural data suggest that faults within the Neapolitan Yellow Tuffs become increasingly unstable with depth and temperature. The breakdown of zeolites and the presence of hot, pressurized fluids contribute to fault cementation, enabling the accumulation of higher elastic strain energy. These insights provide a new perspective on the seismic activity and ground uplift currently observed in the Campi Flegrei caldera.

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Frictional properties of shallow subduction zone fault rocks: insights from the Sestola-Vidiciatico unit, Northern Apennines

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Keywords: megathrust rheology, frictional experiments, faulting mechanisms.

The subduction zones interface are characterized by thrust fault systems that accommodate deformation at convergent plate margins. The frictional properties and healing behavior of subducted fault rocks influence the nucleation and propagation mechanisms of megathrust earthquakes. The Gova Fault Zone (GFZ) is the basal décollement of the Sestola-Vidiciatico tectonic mélange (SV) in the Northern Apennines (Italy), which offers a unique opportunity to examine rock deformation processes within an exhumed subduction channel. The GFZ juxtapose highly folded and strained phyllosilicate-rich rocks from the upper plate hemipelagic sediments (Fiumalbo Shales, FIU, and Civago Marls Fms., CIV) on the foredeep turbidites (Gova Sandstone Fm., GOV) of the lower plate. We collected samples for each lithotype across the GFZ section, from the footwall GOV sandstones, the cemented foliated layer highlighting the basal décollement surface (CFL), and the foliated CIV and FIU, into the SV shear zone. Fault rocks were reduced to gouge and sheared in a rotary shear apparatus with a hydrothermal vessel (ROSA+HYDROS, University of Padua), under 20–60 MPa normal stress, 6 MPa fluid pressure, at 25 °C, 150 °C, and 200°C. We characterized the friction coefficient and healing, calculated as the time-dependent recovery of frictional strength during hold stages. The GOV sandstone gouges have friction coefficient increasing with temperature, from $\mu = 0.49$ (25°C) to $\mu = 0.58$ (150 °C) and to $\mu = 0.59$ (200°C), show positive healing and a transition from stable slip to stick-slip at 200 °C. Microstructural observations on experimental gouge indicate cataclasis as the main deformation process. The CIV marls show $\mu = 0.27$ (25 °C and 150 °C)–0.31 (200 °C), and the FIU shales $\mu = 0.20$ (25 °C)–0.25 (200 °C) and 0.29 (150 °C), with null/negative frictional healing rates. Both maintained stable sliding, facilitated by frictional sliding of phyllosilicate lamellae through crystal reorientation and buckling. The CFL shows intermediate friction $\mu = 0.37$ (25 °C)–0.42 (200 °C), negative healing and stable sliding. The higher frictional strength of the footwall GOV sandstones would, in nature, force strain to migrate towards the weaker lithologies of the hanging wall. The strain distribution within the GFZ support strain localization towards the hanging wall. The positive healing and stick-slip behavior at 200 °C of GOV sandstone implies that, with increasing depth, seismic instabilities can nucleate in the footwall. Conversely, lower friction and lack of frictional healing implies that the phyllosilicate-rich hanging wall deforms mostly aseismically or by slow slip. Collectively, we found that the microstructural (i.e., cataclasis vs. phyllosilicate reorientation), frictional and healing heterogeneities between the subducting sediments and the tectonic mélange at shallow depths may control the nucleation of seismic instabilities in the footwall and the strain migration within the hanging wall of the basal décollement thrust system.

Comparing deterministic and stochastic fracture networks properties with natural fracture networks

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Keywords: DFN, fracture network, models.

Discrete Fracture Network (DFN) models are widely used to predict the three-dimensional distribution of discontinuities in fractured rock masses. In DFN, fractures can be generated stochastically, according to a series of statistical distributions and controlling parameters derived from the actual fracture network sampled in 2D (outcrops) or 1D (boreholes), or deterministically, reproducing the actual position, orientation and size of fractures.

Recent advances in 3D fracture network parametrization in the field or in geophysical datasets are not fully reflected in the processing capabilities of DFN simulators. For example, to the best of our knowledge, no 3D DFN stochastic simulator can generate fracture networks with realistic topological relationships, and it's not possible to model fracture spatial distributions other than a random Poisson distribution (meaning clustered or regular distributions cannot be represented). This results in stochastic fracture networks unable to reproduce realistic connectivity, which significantly affects our ability to model hydraulic properties of fractured rock masses.

In this study we report a comparative study, involving the reconstruction of a real 3D fracture network leveraging micro-CT scan of a highly fractured sample of a fine-grained, laminated diatomitic marl (Miocene equivalent to the Tripoli Fm, Palena, Central Italy). Starting from the CT stack, we built (i) a deterministic fracture network mimicking the reconstructed real one, and (ii) a series of stochastic fracture networks in DFNWorks, based on the fracture parameters sampled at 2D sections of the 3D CT volume, to simulate the typical procedure of DFN generation from outcrop data. The obtained DFNs were used to estimate the hydraulic properties of the studies sample with different semi-analytical (e.g. Oda method) and numerical methods (e.g. finite volumes implemented in DFNWorks).

Our preliminary results highlight the limitations of stochastic DFNs calibrated on 2D sampling planes, and of deterministic DFNs in terms of fracture shape representation and suggest that advanced numerical methods are more sensitive to the quality of input data (e.g. topology and fracture shapes) than simplified semi-analytical methods. This outline the need to refine existing DFN generators towards a more realistic representation of complex real fracture networks.

Structural architecture of the Cretaceous carbonates exposed in the Castelsaraceno area of the Raparo Mt. southern Italy

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Keywords: fracture stratigraphy, southern Apennines, platform carbonates.

The platform carbonates of southern Italy were involved into the multi-stage tectonic evolution of the Apennines, which predominantly consisted in Miocene thrusting (Manniello et al., 2023), and Plio-Quaternary transtension and exhumation from shallow crustal depth depths (Schirripa Spagnolo et al., 2024). In order to document both style and amount of deformation associated either to nucleation and development of intra carbonate thrust faults or to the later growth of high-angle transtensional faults, this study focuses on the Raparo Mt. carbonates units of the Basilicata Region. The study carbonates are exposed along the natural creek and artificial trails of the Castelsaraceno area. There, the Cretaceous carbonates are very well-layered, and form m- to a few m-thick bed packages bounded by cm- to several 10's of cm-thick marly-clayish interlayers. Such a multi-layered succession, after long-lasting burial diagenesis, was first deformed by thrust faults and associated fault-bed folds of the carbonates. At the mesoscale, thrusting and folding were solved by thrust-parallel joints and veins, pressure solution seams at high angles to thrust faults, and low-angle sheared fractures displaying reverse motion. Thrust-related quantitative analysis carried out both in the field and digitally, permitted to compute the values of both fracture density (P20) and intensity (P21) along given 2D outcrops. Results show that both joints and veins are characterized by higher P20 and P21 values within the thrust damage zones, whereas away from the them the fracture network mainly includes N-S and NE-SW striking, high-angle joints and sheared joints. Plio-Quaternay trastension was documented along NE-SW trending faults with throws cm-to-10's of cm, and right lateral component of slip. The smaller displacement fault, ca. 1 cm-throw, is made up of vertically discontinuous slip surfaces forming a conjugate system bounded within single bed-packages. The fault core is almost absent, the damage zone highly discontinuous along dip, and mainly include fault-parallel to vertical NE-SW joints and veins. Considering the latter structural elements, we note that P20 increases in proximity to the slip surfaces, whereas P21 is almost constant. These results are interpreted as due to the nucleation of the transtensional faults, and formation of fault-related fractures in the surrounding of the bed-package bounded slip surfaces. The second study transtensional faults shows a throw variation along dip comprised between 10 and 60 cm, include through-going slip surfaces along which tiny veneers of fault breccia, and mainly fault-parallel joints, sheared joints and veins. Both P20 and P21 computed for the latter structural elements increase proportionally in the vicinity of the slip surfaces. This positive correlation is interpreted as due to fault growth by linkage of pre-existing slip surfaces (> P21), and concomitant formation of new joints and veins (> P20).

Manniello C. et al. (2023) - Pressure solution-assisted diagenesis and thrusting-related deformation of Mesozoic platform carbonates. Journal of Structural Geology, 173, 104906, https://doi.org/10.1016/j.jsg.2023.104906.

Schirripa Spagnolo G. et al. (2024) - Structural architecture and maturity of Val d'Agri faults, Italy: Inferences from natural and induced seismicity. Journal of Structural Geology, 180, 105084, https://doi.org/10.1016/j.jsg.2024.105084.

In search of a geological signature of slow earthquakes: structure and geochemistry of crack-seal veins in metasediments from the Alpine accretionary prism

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Keywords: crack-and-seal veins, slow earthquakes, hydrauilc fracturing.

Metasedimentary rocks exhumed from various depths in subduction accretionary settings are typically infused by systems of mineralized veins, commonly filled by quartz and/or calcite. Their geometric and chronologic relationships with the multiphase deformation history characterizing the host rocks suggest repeated tensile and/or shear hydraulic fracturing at near-lithostatic fluid pressures.

The zones with evidence for high pore-fluid pressures in subduction plate interfaces are in the same depth ranges where the spectrum of slow earthquakes (i low-frequency earthquakes, tremor, slow slip events) are seismologically or geodetically detected: the transition zones between the locked seismogenic zone and the shallow and deep stably sliding zones. This suggests that dehydration and hydraulic fracturing of variably lithified sediments during passage along the plate interface and accretion at the prism base, may represent a possible source for slow earthquakes, thus making mineralized veins possible candidates for structures associated with slow earthquakes (Platt et al., 2024).

Here we report on a detailed structural and geochemical analysis of crack-seal, composite quartz/calcite vein systems in the trench turbidite deposits covering the Ligure-Piemontese ocean-derived units cropping out in the Internal Ligurian Units (ULI) of Northern Apennines and in the Upper Units (UU) of Alpine Corsica. The two groups of units were structured in the same Late Cretaceous-Early Tertiary Alpine accretionary complex but at different structural levels (200-230 °C and 0.6-0.8 GPa for the studied ULI; 150-200°C and 0.3-0.4 GPa for the studied UU).

The structural analyses show the occurrence of distinct episodes of hydraulic fracturing and mineralization – with Mode I and/or Mode II opening mode - evidence of a complex fluid-rock interaction, accompanied by progressive lithification and diagenesis of the turbidite sequence during subduction; that resulted in a continuous evolution of the rheological properties of the turbiditic multilayer. The vein textures clearly indicate multiple episodes of fracture and sealing associated with cyclic build-up of pore fluid pressure.

Preliminary C and O isotope analyses of the vein sets in the UU and in ULI show quite homogeneous $d^{13}C$ e $d^{18}O$ values for all the different sets of veins, suggesting a common fluid origin for all vein sets, no matter their geometric and chronological relationships with the different deformation steps. Particularly, the $d^{13}C$ e $d^{18}O$ values for either the Corsica or Ligurian samples seem to suggest a fluid origin related to decarbonation of calcareous sediments, although some difference in the isotopic signature of the two units groups can be identified. Further investigation will be devoted to deeply understand the isotope trend of host rocks, most probably related to the progressive lithification and diagenesis of the turbiditic section moving along the plate interface.

Platt J.P. (2024) - Geological fingerprints of deep slow earthquakes: A review of field constraints and directions for future research. Geosphere, 20(4), 981-1004, https://doi.org/10.1130/GES02722.1.

Sand injectites and fluid flow in the Magallanes basin in the southernmost Andes

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Keywords: injectites, sedimentary dikes, Magallanes basin.

Sand injectites are soft-sediment deformations that occur in the turbiditic sequences during the early stages of burial in the foredeep and foreland basins. These structures consist of upward intrusion (dykes and sills) and extrusion (sand volcanoes and boils), in many cases genetically related, formed during the remobilisation of depositional sand bodies. Sand dykes and sills developed tens to hundreds of meters above the deep-water depositional sand units from which they are assumed to be sourced. They are known in the outcrops and the oil field boreholes (Duranti & Hurst, 2004). The triggering mechanism for the fluidisation and injection of unconsolidated sand with high porosity, is driven by the fluid overpressure into the marls sediments, generated from depositional-related processes (slumping, erosion, etc.) as well as from tectonic-induced stress (emplacement of thrust sheets, seismicity, etc.) (Jolly & Lonergan, 2002). The Austral-Magallanes foredeep basin extends for more than 1000 km in the frontal part of the Andean Cordillera from southern Patagonia to Tierra del Fuego Island, including the Atlantic offshore. The basin developed on the continental crust and presents a sedimentary wedge, of more than 5.000 m of thickness, consisting primarily of mud-prone marine siliciclastic sediments. The Magallanes foredeep basin has evolved since the Late Cretaceous and migrates progressively towards E and NE and reaches the central part of the Tierra del Fuego, in the Upper Eocene (Biddle et al., 1986). Along the Atlantic coast of Tierra del Fuego, the gently deformed Oligocene-Lower Miocene deep marine sediments with silt-claystone, mudstone and sandstone facies are affected by soft sediment deformation structures where spectacular clastic dikes prevail. Using a combination of field survey and remote sensing techniques, a high-detail geological map has been produced, and a 3d reconstruction of the dikes' geometries has been possible. Several generations of metric to decametric clastic dykes and sills are intruded in the thick claystone. Their geometry consists of subvertical pillars and dykes, low angle conical intrusions of few to many of meters of thickness, generated at the wedge of depositional sand bodies. The lateral extensions span from decimeters to more than 300 meters. The dyke framework presents a polygonal geometry with a primary N-S trend and with a dipping varying from 30° to 90° (Menichetti et al., 2008). The provenance of the intruded sand can be located in the sandstone levels, underlying a few hundred meters, where load casts, flame structures and amalgamations are common structures. The dyke geometries, the stratigraphic unconformities visible in the outcrops as well as displayed in the seismic lines, constrain a triggering mechanism for the upward intrusion process from the sandstone layers, remobilized by E-W transtensional tectonic events, affecting the sedimentary basin since the Oligocene.

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Fault reactivations and fluids: GNSS and seismological analysis in the Peloritani-Aeolian System

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Keywords: fluid–fault interactions, crustal deformation monitoring.

Fluids modify the mechanical properties of rocks, such as shear strength and strain behaviour. We analyze the timing of deformation and the occurrence of seismicity during 2021 along strike-slip fault systems in the Peloritani Mountains (northeastern Sicily) and the Aeolian Archipelago, using GNSS and seismic data. Results reveal crustal-scale deformation along a NNW-SSE trending right-lateral transtensional zone across the Peloritani Mts and its offshore prolongation (here defined as the Gulf of Patti-Tindari-Letojanni Fault System, GPTLFS), as well as in WNW-ESE to NW-SE right-lateral transfer zones in the western and central sectors of the Aeolian Archipelago. In 2021, the eastern sector of the GPTLFS showed an increased deformation rate compared to its western part. This deformation episode coincided temporally with an increased release of seismic strain and the unrest at Vulcano. The latter was characterized by rapid ground inflation and enhanced gas emissions. The temporal correlation between these phenomena suggests that enhanced fluid circulation, evidenced by gas emissions in the Peloritani Mts, may modulate the mechanical response of faults, promoting strain release. These observations improve our understanding of the interactions between tectonic deformation, fluids, and volcanic activity in the region.

Deformation-driven diagenesis in shallow porous carbonates

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Keywords: porous carbonates, deformation bands, diagenesis.

Deformation can have a positive or negative impact on rock strength, stiffness and porosity depending on the initial properties of the rock: porous rocks produce deformation bands (DBs), reducing porosity and permeability, and potentially increasing rock strength and stiffness, while low porosity (tight) rocks produce fractures and faults, enhancing permeability and deteriorating their overall strength and stiffness. We present a field study in two well-exposed ravines near Matera and Gravina in Puglia (Southern Italy), where we document the effects of mild regional deformation on the petrophysical properties of the Plio-Pleistocene porous carbonates of the Calcarenite di Gravina Formation.

Field structural survey allowed us to identify a pervasive network of subvertical deformation bands (DBs) in both sites, mostly striking NNE-SSW. DBs are evenly spaced, and their thickness and density correlate with sedimentary facies, with thinner and denser DBs occurring in fine-grained bioclastic calcarenites and thick, widely spaced DBs in coarser, well sorted units. DBs do not produce macroscopic marker displacement and within DBs grains are not broken but reoriented with the long axis parallel to the DB's boundaries. Therefore, DBs can be classified as disaggregation bands with dilatational/shear kinematics. In situ petrophysical measurements using a portable air permeameter and Schmidt hammer demonstrate that DBs are less permeable and stronger than the host rock. Host rock permeability varies from 2 to hundreds of Darcy, while DBs display permeability as low as 0.2 d. Field petrophysical measurements correlate well with porosity values from image analysis, Hg-intrusion porosimetry, and 3D micro-CT imaging, highlighting a reduction of porosity from above 40% in the host rock to less than 20% in the DBs, with a clear decrease of the mean pore throat in DBs. Optical microscopy, cathodoluminescence and SEM imaging revealed microgranular calcite cement within DBs and HRs, characterized by a bright orange luminescence. In the host rock, the cement constitutes a thin rim surrounding the grains, while within the DBs the cement occupies all the volume between clasts. Stable isotope analyses ($\delta^{13}C$ and $\delta^{18}O$) of host rock and DB cements suggest precipitation from modified marine fluids with varying degrees of meteoric water influence. Cluster analysis of isotopic values supports the interpretation of DBs as preferential sites for early diagenetic calcite cementation under shallow burial conditions.

Integration of geological, petrophysical, and geochemical data suggests that pervasive deformation bands forming in response to mild, far field tectonic stresses can produce significant anisotropy in the porosity, permeability, rocks strength and acoustic properties of shallow porous carbonates. Such anisotropy is likely to be maintained during burial, with DBs acting as low-permeability baffles to fluid flow at the outcrop and potentially reservoir scale.

A multi-method approach to constrain temperature, fluid-rock interaction processes, and fluid evolution in clay-rich fault zones: insights from Lemnos Island (Greece)

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Keywords: X-ray diffraction, stable isotope analysis, K-Ar dating.

Fluid circulation in the shallow crust is controlled by faults, which can act as barriers, conduits, or combined systems. In fault zones, fluids of meteoric, connate, or magmatic/hydrothermal origin vary in temperature and composition, leading to the formation of neoformed minerals in veins and fault rocks (e.g., carbonates, silicates, sulphates, oxides/hydroxides, clays). In limestone-hosted faults, stable (C, O) and clumped isotopes, fluid inclusion microthermometry, and U-Pb dating on carbonates (e.g., slickenfibers, veins) are commonly used to constrain fluid temperature and origin during deformation. In these cases of veins composed by a single neoformed mineral species (e.g., calcite, dolomite), fluid isotope composition can be calculated by a single mineral-water fractionation factor (α). The α-factor accounts for the difference in isotopic composition between a mineral and the water with which it interacts, and it quantifies how isotopes are exchanged as function of temperature. In contrast, fault rocks developed in clay-rich faults typically contain more complex polymineralic assemblages, composed by detrital minerals inherited from the host rocks and authigenic clay minerals (e.g., mixed layers illite-smectite) precipitated from circulating fluids and/or formed by shear heating activated reactions. Also, in clay-rich fault zones, monomineralic veins are hardly observed. Consequently, both detrital and authigenic clay minerals interact with fluids, making fluid source identification more challenging. As a result, isotopic studies of clay-rich fault rocks are generally limited to case studies where samples have nearly monomineralic compositions, typically greater than 90% authigenic components. To address this, we propose an alternative workflow for reconstructing fluid isotopic signature directly from polymineralic fault gouges, codified in our PolyFrac spreadsheet. This approach integrates H and O isotopic data and X-ray diffraction (XRD) analysis of distinct grain-size fractions (from < 0.1 to 10 μm) separated from clay-rich gouges, in combination with K-Ar dating. We investigated two regional-scale extensional faults on Lemnos Island (Greece) - the Kornos-Aghios Ioannis and the Partenomythos faults - affected by Si-rich hydrothermal alteration. Results show that the fault cores developed by mechanical comminution of the host-rock in the presence of hydrothermal fluids, and later evolved into a system dominated by meteoric infiltration, leading to the precipitation of authigenic clay minerals from ~16 Ma onwards. Our result show that this multi-method approach allows the reconstruction of time-constrained models of fluid evolution in clay-rich fault zones, offering a valuable reference for similar studies in other geological and tectonic settings.

Carbonate concretion patterns as proxy for paleo-fluid flow and diagenetic processes affecting high-porosity sandstone reservoir analogue (Crotone forearc Basin)

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Keywords: structural diagenesis, carbonate concretions, fluid flow pathways.

Diagenetic processes heavily impact the efficient exploitation of strategic fossil resources (oil and gas), preservation and management of aquifers, and underground storage of anthropogenic CO_2 and H_2. The study of selective cementation of high-porosity sandstone bodies is crucial to the understanding of reservoir quality. The analysis of cementation patterns at the outcrop scale could unravel fossil fluid flow pathways affecting siliciclastic sandstone sequences.

We present the results of a study focused on selective cementation of fluvio-deltaic, Pliocene age, sandstone to conglomeratic bodies exposed in the Crotone forearc Basin, South Italy. The siliciclastic unit was deposited in a shallow marine setting and reaches a maximum thickness of ~200 m, unconformably overlying the Paleozoic Sila Massif metamorphic basement. The sandstone sequence is almost completely devoid of any primary diagenetic cement thus appearing nearly incohesive. The studied outcrops show a gentle tilting of sandstone beds towards SE, with mild brittle deformation in the form of deformation bands and subsidiary faults. Selective cementation can be traced as diagenetic concretions of different shapes and sizes. Concretion types comprise tabular-lens shaped bodies laterally extensive up to 10's m, elongate blade-shaped objects from 10 cm up to several 10's meter-long, asymmetric drop-shaped concretions and nodular-spherical bodies. The elongation direction of concretions parallels the southeastward dip of bedding, except in the vicinity of deformation bands and faults, where elongate concretions are vertically oriented. The selective cementation was due to pervasive calcite precipitation, which caused a dramatic porosity loss from 25-30% down to 2-3%, leading to a significant increase in sandstone cohesion and stiffness. Tightly cemented bodies enclose deformation bands and host 2-3 sets of joints which abut at the concretion-host rock boundary. Cold cathodoluminescence analysis revealed the extensive presence of yellow-bright, granular to poikilitic calcite cement within concretionary bodies. Carbon and Oxygen stable isotopes performed on calcite cement suggest two different sources responsible for the selective cementation. The first source can be traced in weakly cemented lens-shaped bodies and along secondary faults and is made of mixed marine-meteoric fluids with contributions from soil percolation. Conversely, the second source can be detected in tightly cemented lens-shaped and nodular to elongate concretions and is given by a mix of marine fluids with contributions from biogenic methane likely related to biological-bacterial activity in a shallow marine setting. The evolution of fluids from meteoric to marine ones can be associated with progressive sea level rise and a marine transgression phase that occurred after sandstone deposition.

Spontaneous complexity in the dynamics of slow laboratory earthquakes

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Keywords: earthquake, nucelation, heterogeneity.

Rock deformation experiments play a key role in our understanding of earthquake physics and friction constitutive laws. These laws commonly describe the response of analogue laboratory faults as a simple and homogeneous system, without accounting for the spatial-temporal evolution of structures in the sample. However, increasing experimental evidence suggests that slip instability is closely tied to heterogeneity, complex rheologies, and inhomogeneous boundary conditions. To address this, we designed a novel transparent setup to observe real-time deformation, track the spatial-temporal evolution of shear fabric, and document unstable slip in experimental faults. Our video documentation reveals that the progressive development of fault fabrics results in heterogeneous but not random stress redistribution. We show that stress and structural heterogeneities play a key role in the nucleation, propagation, and arrest of slip instabilities, raising questions about the robustness of scaling laboratory frictional laws to nature.

Fracture pattern in thermo-metamorphic marbles: the case study of Campiglia Marittima Marble (Northern Apennine)

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Keywords: brittle deformation, structural geology, joints.

Motivated by the paucity of studies on fracture networks in thermo-metamorphic rocks, in this work, we present a detailed fracture study in the Campiglia Marittima Marbles (CMM), located within the thermo-metamorphic aureole around the top of the Botro ai Marmi Granite pluton (BMG), in central-western Tuscany, part of the Northern Apennines (Giannini, 1955). We combined traditional field structural geology techniques, with digital analysis of a 3D model built by means of photogrammetry using drone images. Our study reveals a predominant component of radial and concentric fractures around the top of the BMG pluton. This pattern evidences a strong control of the ascent of the magmatic body on the fracture development (Koide & Bhattacharji, 1975). We also observe that ductile deformation related to the pluton emplacement is post-dated by fractures. Accordingly, we deduce that fracture orientation reflects the local stress field active during the final phase of pluton ascent, when the host rocks had already cooled.

Our results provide insights into fracture pattern architecture and related deformation processes in thermo-metamorphosed rocks associated with magmatic emplacement.

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Fluid inclusion analysis of minor Calcite veins in the fault zone of the Gubbio normal fault (central Italy)

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Keywords: fluid inclusions, active faults, seismicity.

This study investigates the composition of fluids circulating in the footwall block of the Gubbio normal fault (GuF), a seismically active normal fault, characterised by a complex, multiphase tectonic history (e.g. Mirabella et al., 2004), to better understand fluid flow mechanisms in active fault systems. The study is focused on syntectonic calcite veins hosted in different geological formations in the GuF footwall, with the aim of comparing, for the first time, the fluid composition of these minor veins with those of the main GuF surface, previously studied by Bussolotto et al. (2007) and Marchesini et al. (2022), to assess whether they share a common origin and migration mechanisms. Furthermore, the study explores whether minor faults, similar to those activated during recent seismic sequences in the hanging wall of the Alto Tiberina Fault, can also act as fluid pathways. Previous studies reported fluid temperatures between 60-185 °C along the GuF main fault. Bussolotto et al. (2007) found values of 60-65 °C and 70-80 °C, while Marchesini et al. (2022) recorded higher values up to 185 °C. To expand on this, nine samples were collected for fluid inclusion analysis, from three stratigraphic units (Scaglia Bianca, Scaglia Rossa, and Scaglia Variegata) across different sectors of the GuF. Petrographic and microthermometric measurements were carried out at the Norwegian University of Science and Technology (NTNU, Trondheim) on aqueous biphase inclusions, focusing on homogenization temperature (Th) and ice melting temperature (Tmice). Most samples showed evidence of intracrystalline deformation of calcite, with inclusions affected by decrepitation and necking-down, making it difficult to distinguish between primary and secondary inclusions. As a result, we identified secondary inclusions by their trail patterns, while the rest were grouped under "other petrography." The dataset reveals significant variability in both Th and salinity, suggesting a complex fluid history influenced by lithological properties and post-entrapment processes. Th values range from 60 to 165 °C, with two main clusters: one at 70-90 °C (modal peak at 70–85 °C), and another at 125-130 °C and 140-145 °C, mostly in Scaglia Bianca. Scaglia Rossa samples, particularly from faulted zones, span a wider range (70-145 °C), indicating stronger re-equilibration. Scaglia Variegata inclusions show only lower temperatures (< 100 °C). Secondary trails display a narrower Th range (65–70 °C), possibly marking a distinct fluid influx. Salinity ranges from 1-5.5 wt.% NaCl. Lower values (1-2 wt.%) may reflect a meteoric source, while higher salinities (5–5.5 wt.%) - mainly in Scaglia Bianca - are plausibly related to fluid interaction with evaporitic layers. Trails consistently show salinities of 3–3.5 wt.%, supporting their secondary nature. The relatively undeformed state of Scaglia Bianca crystals plausibly preserved higher-temperature inclusions, unlike the more deformed and impermeable Scaglia Rossa, which may have hindered fluid flow. In conclusion, the results point to a multiphase hydrothermal system shaped by fluid mixing, structural deformation, and lithological contrasts, with Scaglia Bianca playing a key role in channelling hotter, more saline fluids.

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Fluid assisted faulting in a shallow megathrust shear zone of the Northern Apennines (Italy): constraints from structural and geochemical analyses

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Keywords: megathrust shear zone, fluid circulation, Northern Apennines.

Megathrust shear zones are weak interplate faults localizing deformation under low shear stress and in presence of active fluid circulation. Mineral-filled fracture networks in their damage zones, formed in response to multiple shear and extensional failure events, provide valuable insights into paleostress orientations and fluid characteristics over time.

The Sestola-Vidiciatico Tectonic Unit (SVU) in the Northern Apennines represents a fossil analogue of a shallow subduction megathrust-zone mélange. It is interpreted as the plate boundary shear zone (200-400 m thick) between the Ligurian prism and the underthrusting Adria microplate during early-to-middle Miocene, active at temperatures up to 170 °C. It is composed of kilometre-sized tectonically juxtaposed slices of marls, shales, sandstones and mud-rich deposits. The mélange, formed by slope sediments along with Ligurian Units incorporated at the toe of the prism, was overthrusted along a basal décollement onto the younger foredeep turbidites of Adria microplate.

A mesoscale structural analysis was conducted on a well-exposed segment of the basal contact, along a south-dipping thrust ramp of the SVU. Early soft-sediment deformation in the hanging wall involving polygonal normal faults, led to pervasive flattening foliation and secondary shear surfaces. With progressive lithification, shear localized onto a few dominant thrusts lined by thin calcite shear veins. Along the footwall ramp, unfavourably oriented shear surfaces were gradually abandoned as slip localized along a sharp, smooth, and planar slip surface, incorporating slices of the hanging wall to the footwall. The deformation within the footwall includes an oblique cleavage, minor bed parallel shear planes, and a conjugated set of NNE-SSW left-lateral and N-S right-lateral subvertical transtensional faults. The latter mutually crosscut with the basal thrust of the SVU and are mineralized by two main calcite phases, an early-stage calcite rich in host-rock inclusions and a later inclusion-free calcite. Stable isotope data indicate that mineralizing fluids in both the SVU and the footwall turbidites were mostly in isotopic equilibrium with the host-rocks, except for the inclusion-free calcite sampled along the main décollement, which shows a negative shift in $\delta^{13}C$.

Overall, we documented a marked contrast in deformation style and stress state between the SVU and the footwall turbidites. Our preliminary data suggest that ruptures along the main décollement allowed the ingression of an external fluid likely facilitated by a low-stress environment combined with high fluid pressures. Further geochemical and thermometric investigations will be performed to better constrain the interplay between stress state cycling and fluid circulation in this fossil shallow subduction settings.

Multiscale interactions of deformation, fluid flow, and diagenesis in sedimentary basins

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Keywords: deformation, diagenesis, fluid flow.

We explore the connection between deformation, fluid movement, and diagenesis in sedimentary rocks and basins, from the scale of individual grains and pores, to vast fault systems that delineate entire sedimentary basins and rift systems. Drawing upon global outcrop examples, we illustrate how selective, structurally controlled diagenesis occurs at various scales, highlighting key processes and their implications for subsurface predictions. At the lower end of the scale, we consider the impact of grain-scale deformation on permeability, fluid flow, and fluid-rock interactions in granular rocks. On a larger scale, we examine the interplay between deformation, fluid flow, and diagenesis in basin-bounding fault systems within rift basins. Finally, we demonstrate the importance of understanding structural elements as part of broader structural networks, suggesting that quantitative analysis of network properties could enhance our ability to understand and predict structurally controlled fluid flow in the subsurface.

Structural control on fluid flow history and paragenesis along a basin bounding fault system

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Keywords: deformation, diagenesis, fluid flow.

Within syn-rift basinal settings, the juxtaposition of rift-related clastic deposits in the hanging wall of basin-bounding normal faults against a footwall of crystalline basement is a recurrent structural setting where plays for hydrocarbon exploration or carbon storage can be found. Here, fault-controlled fluid flow can significantly influence and change the petrophysical properties of the fault zone and host rocks over time by means of mineralization and cementation, ultimately controlling fluid pathways. Investigating the timing and extent of fluid flow along major faults permits us to better understand the host rock properties and if these can potentially be favourable for subsurface extraction and storage.

We present a detailed investigation of the timing and paragenesis of fluid flow along the Helmsdale Fault (NE Scotland). The Helmsdale Fault bounds the western side of the Inner Moray Firth Basin, which developed during rifting in the Late Jurassic. The hanging wall consists of the Late Jurassic Helmsdale Boulder Beds that are made of an alternating succession debris flow to fault scarp deposits, whereas the footwall is composed of the Helmsdale Granite. There is ample evidence of paleo-fluid flow along the Helmsdale Fault in the form of calcite cementation and widespread calcite veining in both the hanging wall and in the footwall, locally making up to 5 m thick fault cores of stacked crack-seal veins. U-Pb calcite dating of fossils, veins and cements shows a n initial fluid flow event that quickly follows diagenesis in the hanging wall and spans from 147 to 113 Ma, followed by a later reactivation of the fault system between 86-60 Ma. The spatial distribution of the dated calcite veins shows a clear localization over time of fluid flow along the main faults within the footwall.

Carbonate stable isotope analysis, combined with the salinity of the fluid inclusions in the calcite veins, reveals a marine fluid composition of the calcite vein network over time, irrespective of the structural domain within the fault zone. Clumped isotope thermometry shows a gradual temperature increase towards the footwall (35 to 65°C). The variability in the data suggests that two fluid pathways were active at different moments in time, with one being locally sourced in the hanging wall sediments, and the second percolating upwards along the main faults within the Helmsdale Granite. Occurrence of calcite veins derived from meteoric fluids is documented in the youngest dated vein network (60 Ma) and likely related to the later stages of regional uplift.

Our results suggest that the evolution over time of the petrophysical properties of the hanging wall with progressive mineralization and cementation exert a critical control on future fluid pathways as well as localization and style of subsequent fault deformation.

Heterogeneous strength and healing behaviour in serpentinite shear zones at shallow hydrothermal conditions

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Keywords: serpentinites, experiments, friction.

Serpentinites are "weak" rocks common in several geodynamics settings, including mid-ocean ridges, transform faults and subduction zones. Because of this, serpentinites play a pivotal role in the nucleation and propagation of slow slip events, non-volcanic tremors and tsunami earthquakes.

We studied serpentinites pertaining to the exhumed Monte Fico shear zone (Elba Island, Italy) that reached greenschist facies conditions during deformation. The shear zone, tens to hundreds of m thick, is made of 10-100 cm lenses of massive retrograde serpentinites, mainly composed by the lizardite and chrysotile, wrapped by foliated serpentinites. Bulk deformation is accommodated by anastomosing and pervasive S/C foliations. The lenses are bounded by 1-3 cm thick brittle faults decorated by slickenfibers composed of chrysotile and polygonal serpentine.

To determine the frictional and healing properties of the serpentinite-bearing shear zones and faults under realistic ambient shallow-subduction conditions, we performed 45 slide-hold-slide experiments at $\sigma'n$ = 20 MPa, Pf = 6 MPa, V_{shear}= 10 μm/s and at temperatures from 25°C to 400°C. We sheared with a rotary shear apparatus equipped with a hydrothermal vessel (ROSA-HYDROS, Dept. of Geosciences, UniPD, Italy) the powders obtained from lenses and from slickenfibers.

Regarding the frictional properties of the lenses, when the water is in a liquid state, the friction coefficient increases from 0.3 at 25 °C to 0.5 at 300 °C; when water is in vapour and supercritical states, the friction coefficient is strain hardening (0.6-0.89 at 300 °C-400 °C). Stick-slip behaviour (i.e., seismic slip) is observed only at 400°C. In the case of slickenfibers, when the water is in liquid state, the friction coefficient increases from 0.23 at 25 °C to 0.34 at 300 °C. When water is in vapour conditions the friction coefficient is 0.47 at 300 °C and 0.57 at 400 °C. In conclusion, "lenses" can deform by aseismic creep or seismic slip and "slickenfibers" deform by aseismic creep.

Regarding the frictional healing properties, it differs between lenses and slickenfibers. Frictional healing of the "lenses" is positive and increases with temperature, independently of the physical state of water. Instead, frictional healing of the "slickenfibers" is negative for nearly all the conditions, with a maximum positive healing between 150 °C and 250 °C. In conclusion, the frictional healing properties are consistent with the capacity of the "lenses" to deform by aseismic or seismic slip, while "slickenfibers" by aseismic slip.

Our results show that the frictional response of low-grade serpentinites sheared in the laboratory at shallow-subduction hydrothermal conditions is controlled by the mineral assemblage and temperature. As a consequence, in nature the frictional and healing behaviour is highly heterogenous. At the investigated conditions, low-grade serpentinites can be frictionally unstable and nucleate earthquakes (seismic slip) and slow slip events (creep).

Genesis of Natural Hydrogen by Hydrothermal Alteration of Tuscan Peralkaline Granites

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Keywords: natural hydrogen, hydrothermal systems, peralkaline granites.

Natural hydrogen can be generated through fluid–rock interactions, particularly via the reduction of water by oxidation of Fe^{2+}-bearing minerals. Among these reactions, the serpentinization of Fe-rich olivine in ultramafic rocks is the most extensively studied. However, a less explored but potentially significant source of natural H_2 is the hydrothermal alteration of peralkaline granites. In such systems, H_2 may form through the oxidation of Fe^{2+}-rich biotite, accompanied by the neoformation of Fe^{3+}-bearing minerals such as chlorite or magnetite. Additionally, at lower temperatures, the hydrothermal alteration of magnetite within peralkaline granites may produce H_2 via oxidation of H_2S under acidic conditions, leading to magnetite pyritization, or through direct oxidation of magnetite to hematite.

This study, which is part of NHEAT (Natural Hydrogen for Energy trAnsiTion) project, funded by the Italian Ministry of University and Research (MIUR) under the PRIN PNRR 2022 program, investigates the potential for natural H_2 generation from peralkaline granites in Tuscany, where hydrothermal alteration is active. Tuscany is characterized by a high heat-flow anomaly linked to Late Miocene-Pliocene granite intrusion associated with the opening of the Tyrrhenian back-arc basin, which is currently exploited in the Larderello geothermal field.

Combining multi-scale structural, mineralogical, and geochemical analyses, we examine the hydrothermal alteration of peralkaline granites exposed in the Gavorrano and Botro ai Marmi areas. Micro-Raman spectroscopy of fluid inclusions within quartz grains - present in fault-related sulfide mineralization and chloritized granites - reveals the trapping of molecular hydrogen (H_2).

These findings demonstrate that hydrothermal alteration of peralkaline granites can generate natural hydrogen. Future perspectives required to quantify rate and volume of hydrogen production will be discussed with the final goal of assessing the potential for economic exploitation of H_2 in this region.

Hydrothermal fluid flow along the Yangsan Fault, South Korea

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Keywords: hydrothermal fluids, earthquake, clay-rich fault core.

Clay-rich fault cores are traditionally regarded as long-term barriers to fluid flow; however, recent studies suggest they may be transiently crossed and permeated by fluids during seismic events. Here we present structural, microstructural, and geochemical evidence from three key exposures of the seismically active, strike-slip Yangsan Fault (South Korea), revealing fossil records of earthquake-induced hydrothermal fluid flow within its clay-rich fault core. Multiple generations of calcite veins, slickenfibres, and stylolites document episodic cycles of coseismic fluid influx, fracture sealing, and slow interseismic deformation over seismic cycles. Stable and clumped isotope analyses of syn-tectonic calcites indicate high-temperature precipitation (up to ~130°C) from fluids with a mixed meteoric-hydrothermal origin, in thermal disequilibrium with the maximum burial temperature experienced by the Yangsan Fault (< 90°C). We suggest that deep and warm hydrothermal fluids rose upward and mixed with cold meteoric-derived groundwater through transient permeability pathways generated during coseismic fracturing. Our findings demonstrate that clay-rich fault cores can intermittently facilitate along fault fluid flow during seismic slip, with critical implications for fault seal integrity during geological times, impacts on past hydrocarbon migration pathways, and on seal assessments in future CO_2 and H_2 geological storage in seismically active tectonic settings.

Structural and stratigraphic control on fluid flow in offshore anticlines in fold-and-thrust belts: insights from the Mt. Conero anticline, Italy

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Keywords: fractured carbonate reservoir, CO_2 storage, geothermal reservoir.

We investigate the structural control on paleofluid flow in the Mt. Conero anticline, Italy, located in the frontal part of the Apennines fold-and-thrust belt. This anticline can be considered as an exhumed analog for buried anticlines in the Adriatic offshore, currently exploited as hydrocarbon reservoirs and potential geothermal reservoirs or CO_2 storage sites in the future. By integrating field structural analyses, stable and clumped isotope geochemistry of carbonates, and U-Pb geochronology, we demonstrate that the structural evolution of the Mt. Conero anticline in a carbonate-siliciclastic succession is marked by: (1) pre-orogenic normal faulting and veining likely during foreland flexure, (2) layer-parallel shortening during early contraction, with the development of *en-echelon* bed-perpendicular conjugate veins and stylolites, (3) syn-folding thrusting and strike-slip faulting, and (4) transtensional faulting during fold exhumation and extensional collapse. Fluid circulation took place in a closed system, predominantly involving formation water, such as marine or pore water trapped during diagenesis. Effective sealing by clay-rich formations overlying the fractured, permeable carbonates, coupled with low displacement strike-slip faults and thrusts, prevented the ingress of meteoric fluids and/or the upward migration of deep (hydrothermal) fluids. Limited mixing between formation and meteoric waters in a semi-closed system was observed during fold exhumation and extensional collapse. Our results show that folds in the frontal part of offshore fold-and-thrust belts are likely to retain fluids trapped during diagenesis due to the preservation of sealing layers. This suggests that such anticlines can preserve hydrocarbon reservoirs and are excellent candidates for CO_2 storage due to their low leakage potential, offering also good storage capacity for geothermal fluids. These results may represent a benchmark for offshore anticlines in the frontal part of other offshore fold-and-thrust belts, particularly those with carbonate anticlines overlain by clay-rich sealing layers.

Stress versus damage-induced permeability anisotropy under true triaxial stress states in Etna Basalt

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Keywords: triaxial stresses, anisotropy, permeability.

Fluids within low-porosity rocks are transported through networks of interconnected microcracks and fractures. Under crustal conditions, rocks are subjected to true triaxial stress states characterized by three unequal principal stresses, where $\sigma1>\sigma2>\sigma3$. These triaxial stress states can influence the magnitude and direction of fluid flow in two ways. First, cracks may open, close, and/or slip depending on their orientation with respect to the anisotropic stress field, and thereby potentially reducing fluid flow in certain directions while enhancing flow in others. Second, once the magnitude of differential stresses surpasses the onset of dilatancy in the rock, new cracks form, providing additional pathways for fluid transport. The geometry of these new fractures, and therefore the direction of fluid flow enhancement, is also controlled by the anisotropic stress field.

Despite the fundamental role of triaxial stresses in controlling the magnitude and direction of fluid flow through the crust, very little is known regarding the anisotropy of permeability under true triaxial stress states. This knowledge gap exists primarily because experimental permeability measurements are typically conducted under axisymmetric stress states ($\sigma1>\sigma2=\sigma3$) with fluid flow and permeability usually measured only parallel to the $\sigma1$-direction. To address this, we have developed a new True Triaxial Apparatus (TTA) at UCL equipped with a pore fluid system to deform cubic, saturated rock samples under true triaxial loading while contemporaneously measuring permeability along all three loading axes and recording the output of acoustic emissions (AEs) hits. Results from tests conducted on 50 mm isotropic cubes of initially isotropic Etna basalt under true triaxial loading indicate that, under relatively low differential stresses (< 180 MPa), fluid flow is reduced by over one order of magnitude in the direction parallel to $\sigma1$. Increasing the magnitude of stresses along the $\sigma2$ axis also results in a decrease in permeability along the same axis, although less pronounced. The increase of differential stresses eventually leads to an increase in AE hits, which further coincides with a sharp increase in permeability along the $\sigma2$-axis of one order of magnitude and, to a lesser extent, along the $\sigma3$-axis.

We have recognised a key differentiation in the magnitudes and orientations of permeability anisotropy before and after the onset of dilatancy. One stage is stress-controlled (involving the closing and slipping of pre-existing cracks), while the other is damage-induced (with the formation of new cracks or damage), resulting in entirely different permeability behaviours in these two stages.

Normal fault linkage across relay ramp: geometry and kinematics of the Monte Capo di Serre fault zone

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Keywords: localized deformation, normal faulting, Central Apennines.

Normal fault zones are characterized by a structural architecture that is function of the rock rheology, burial depth, and amount of deformation; in this regard, the geometry of the interacting slip surfaces may affect the style of localized deformation (Scholz, 2019). Focusing on relay ramps, which form due to the lateral propagation and possible linkage of neighboring slip surfaces, we study the Monte Capo di Serre Fault (MCSF), which cut across the Lazio-Abruzzi carbonate platform. MCSF is ca. 8 km-long, shows up to ca. 110 m of throw, and displaces Triassic-Jurassic shallow-water carbonates as well as Cretaceous scarp-to-basinal carbonates (Servizio Geologico d'Italia, 2006). At a large-scale, MCSF is characterized by an undulated trace line, which is reflected in the field by the morphology of the single slip surfaces. Thanks to the beautiful outcrops continuously exposing MCSF along strike for about 800 m, we investigate the attitude of both slip surfaces and slip vectors such as striae and slcikenfibers to unravel any possible variation of fault geometry and kinematics within relay ramps. In the field, the trace length of the surveyed slip surfaces varies between ca. 5 and 50m. These surfaces crosscut Lower Jurassic dolomitic limestone and dolostones and, in places, Pleistocene slope debris. The fault rocks consist of cm- to several cm-thick carbonate cataclasites including mm-thick ultracataclasites, and mm- to cm-thick sheared slope debris. The slip surfaces consist of polished slickensides trending ca. NW-SE, and show a transport direction towards SW, which is similar to the regional framework (Roberts & Michetti, 2004). On the basis of the ca. 200 measured slip vectors, we document pure dip-slip kinematics. In fact, independently of their strike direction, the MCSF slip surfaces mainly solved extensional deformation (main pitch angles 81-91°). However, we note that these data may vary at specific sites. For this reason, we focus on two specific relay ramps, respectively due to dextral and sinistral stepping of the interacting slip surfaces. The first zone is characterized by an overlap of ca. 13 m, and a separation of ca. 2 m. There, the more external (towards the base of the mountain slope) slip surface veers towards a N-S direction, and shows slip vectors trending toward west, hence still consistent with a pure dip-slip extension (pitch 87°). The second relay ramp zone shows a separation of ca. 13 m, an overlap of ca. 27.5 m, and includes a ca. 3 m-thick volume of slope debris displaced by multiple slip surfaces trending NW-SE to E-W. The E-W surfaces display slip vectors trending towards SE, which is consistent with an oblique-slip, left-lateral normal faulting (pitch ca. 54°) due to the local σ2-σ3 stress axes permutation (Fossen, 2010). These results are key to better understand the outcomes of ongoing roughness analysis conducted along the same study slip surfaces.

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Multiphase deformation of a serpentinite shear zone in Eastern Elba Island, Italy

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Keywords: serpentine, faults, fluids.

Serpentinites in the Eastern Elba Island give us insights into the deformation processes and about the mechanics of these rocks at different conditions: from shear during compressional tectonics, to exhumation and dismemberment during extensional tectonics.

The serpentinite body (top of the Complex II of Trevisan 1950) is a shear zone cropping out in the eastern part of the Elba Island (Tuscany, Italy) and it is interposed between two tectonic units of continental affinity. The shear zone has a maximum thickness of about ~100m at the Mt. Fico quarry, which is the focus of this study. The shear zone it is composed of serpentinized lherzolites and hazburgites, with local very small intrusions rodingites. The internal architecture of the shear zone is arranged in S/C-C' geometry with lenses of massive metaperidotite bounded by brittle fault surfaces. Massive serpentinite lenses range in size from cm to meters and show typical retrograde pseudormorphic massive textures whereas fault surfaces are mostly coated by chrysotile and polygonal serpentine slickenfibers.

Most of the low angle S/C-C' fabrics and slickenfibres show top-to-E-NE sense of shear and are coonsistent with the compressional emplacement of the serpentinites during the Apennine orogeny but also discordant with the contacts of the tectonic unit. These fabrics reveal the shear zone mechanics of deep serpentinites under greenschist and perhaps blueschist facies deformation conditions: deformation is accommodated mostly by slip along weak anastomosing brittle faults, coexisting with fracturing and pressure-solution compaction in the surrounding massive lenses. This mode of deformation suggests fluid pressure cycles and intermittent brittle slip accompanied by dilatation hardening, which may represent the mechanism for bulk slip during slow slips and earthquake nucleation in subduction zones.

We also document extensional low-angle fabrics with rather dispersed slip directions (ttS-SE and ttW) that rework and re-fold older ttE fabric. These fabrics, even though ubiquitous, form distinct secondary shear zones that are more evident toward the limits of the shear zone with the surrounding units. We interpret these extensional shear zones as the detachment structures that guide the exhumation of the serpentinite slice. Late, high-angle normal and trastensional faults cut all the pre-existing low-angle fabrics and show serpentine, calcite and quartz mineralizations. Along these structures and along some low-angle fabrics, we also observe static oxide staining of fault surfaces and the extensive presence of antigorite in whitish bands, in particular along the E/SE, high angle contact of the shear zone. This suggest the activity of high-angle normal/transtensional faults during the emplacement of the Porto Azzurro Pluton and the extension of its contact metamorphism well within the serpentinites.

Coseismic frictional melting at fluid-rich conditions: inferences from a pseudotachylyte-bearing fault in cherts (Inuyama, Japan)

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Keywords: pseudotachylyte, chert.

Frictional melting and thermal pressurization are processes proposed as coseismic fault lubrication mechanisms. In fluid-rich environments, frictional melting should be hampered by thermal pressurization, because high fluid pressure reduces friction and prevents the fault from reaching the high (> 1000 °C) temperature required for melting. Yet, pseudotachylytes (quenched coseismic frictional melts) have been found along some exhumed megathrusts and splay faults in accretionary complexes characterized by high fluid content. To understand how frictional melting occurs in fluid-rich rocks we studied a pseudotachylyte-bearing thrust fault hosted in black/grey cherts of the Jurassic accretionary complex of Inuyama (central Japan) (Ujiie et al., 2021).

The pseudotachylyte consists of a 2–3 mm thick black layer developed by preferential melting of black carbonaceous mudstone (comprising illite, chlorite, pyrite, quartz and carbonaceous material) interbedded with fractured cherts. Clasts of chert, quartz and rare chloritic and illitic mudstone fragments are dispersed in a matrix of submicrometric phyllosilicates. Sharp selvages with truncated grains, embayments exploiting chlorite veins in the wall-rock cherts, highly vesicular matrix, clasts with corroded margins, and an increase in crystallinity of the carbonaceous material, altogether indicate an origin by frictional melting. Locally the pseudotachylyte is layered with Fe-poor and Fe-rich zones separated by gradational contacts, with Fe-rich zones located in or near brecciated dilatant domains. Centimetric injections with angular clasts cemented by colloform Fe-oxides intrude the wall rock. Pyrite in the black mudstone is locally substituted by Fe-oxides at the selvages of the pseudotachylyte and along the injections, with only rare, corroded pyrite fragments preserved. Conversely, pyrite is stable and Fe-oxides absent just at a few millimetres away from the pseudotachylyte. Pyrite dissolution concomitant with Fe-oxides precipitation implies a change in redox conditions localised along the fault plane that we infer to be coseismic.

We propose that these observations reflect the microstructural record of coseismic slip at fluid-rich conditions. We suggest this sequence of events: (i) initial fluid pressurization associated with slip acceleration and a change in redox conditions; (ii) wall-rock brecciation promoted by thermal fracturing and high fluid pressure, leading to local and instantaneous pressure drops and precipitation of Fe-oxides; (iii) local recovery of frictional strength favouring frictional melting; (iv) melt quenching and continued precipitation in the dilational sites. This sequence of coseismic events explains how frictional melting can be achieved in presence of fluids, in accordance with experimental works (Brantut, 2020). Recognising these processes in the geological record is relevant to investigate coseismic slip weakening and the earthquake energy budget in wet conditions.

Brantut N. (2020) - Dilatancy-induced fluid pressure drop during dynamic rupture: Direct experimental evidence and consequences for earthquake dynamics. Earth and Planetary Science Letters, 538, 116179.

Ujiie K. et al. (2021) - Frictional melting and thermal fracturing recorded in pelagic sedimentary rocks of the Jurassic accretionary complex, central Japan. Earth and Planetary Science Letters, 554, 116638.

The influence of cementation on the frictional stability of faults

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Keywords: fault healing.

Fault healing is a crucial mechanism for the seismic cycle allowing faults to lock and restrengthen during the interseismic time. Several studies suggest that the rate of fault healing controls the magnitude and recurrence time of earthquakes both in laboratory and in nature. Experimental works show that fault healing, at the time-scale of the laboratory approach, derives from the time-dependent growth of the frictional contact area due to plastic flow at the contacts. However, natural seismic cycles, respect to laboratory ones, show considerably longer interseismic times, during which mechanisms such as cementation and pressure-solution are more effective as supported by the widespread presence of cataclasites within several fault cores. Nevertheless, laboratory studies on the role of cementation on fault stability are still few. Here, we present the results of a laboratory work investigating how cementation and frictional healing influence the fault slip behavior of laboratory faults made of hydraulic cement. Cementation, unlike frictional healing, results in larger and non-linear healing, which ultimately promotes unstable slip. Microstructural analysis on wet samples shows the precipitation of minerals expected from the cementation reaction. Our results show that cementation induces a time-dependent increase of fault cohesive strength that scales with time as the stress drop. We suggest that cementation is a fundamental mechanism for fault healing during interseismic time, which influences the seismic potential of faults, even at shallow depths, with relevant implications for natural and induced seismicity.

S10.

Integrated seismotectonics, earthquake geology and modeling: geological and geophysical perspectives on the active tectonics of the Mediterranean region

CONVENERS AND CHAIRPERSONS

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Defining a new 3D "a-priori" model of seismic velocity for the Emilia region

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Keywords: Emilia, seismic velocity, seismicity.

This study presents the development of a new three-dimensional seismic velocity model of the crust and upper lithosphere for the Emilia region, located in Northern Italy. The objective is to enhance the imaging of subsurface geological structure and to better understand the seismotectonic processes acting in this tectonically active area.

The Emilia region is characterized by high quality seismic data, also including the major 2012 seismic sequence (Maximum magnitude 6.1; Carannante et al., 2015), a good coverage of temporary and permanent seismic stations, and the availability of several investigations dealing with the crustal structure imaging. On these grounds we propose a methodology relying on the integration of seismological datasets and other geophysical information typically used in both earthquake and exploration seismology. The data sources include high-quality reflection seismic profiles, results from previous tomographic studies, Moho depth estimates, and additional structural constraints derived from both active and passive seismic investigations.

A semi-automated procedure, previously validated in Southern Italy (Orecchio et al., 2011), is adapted and further refined in this study to derive an initial 3D "a-priori" P-wave velocity model for the Emilia region. This method allows us to evaluate the consistency across different datasets and to define a more accurate starting model for further seismic analysis.

In particular, the "a-priori" velocity model used as initial input for future local earthquake tomography will enable high-resolution imaging of subsurface heterogeneities and it may help in better identifying active fault systems and seismogenic structures.

Orecchio B. et al. (2011) - Imaging the velocity structure of the Calabrian Arc region (southern Italy) through the integration of different seismological data. Bollettino di Geofisica Teorica ed Applicata, 52(4), 625-638, https://doi.org/10.4430/bgta0023.

Carannante S. et al. (2015) - The May 20 (MW 6.1) and 29 (MW 6.0), 2012, Emilia (Po Plain, northern Italy) earthquakes: New seismotectonic implications from subsurface geology and high-quality hypocenter location. Tectonophysics, 655, 107-123, https://doi.org/10.1016/j.tecto.2015.05.015.

First geology-based multi-scale Quaternary stress maps along Peninsular Italy's seismic heartland

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Keywords: high resolution stress map, plate tectonic forces, maximum horizontal stress.

We present the first geology-based, multi-scale stress maps derived from ~8,000 Plio-Quaternary fault-striation pairs across Peninsular Italy's seismogenic extensional belt. Stress-field inversions were performed at structural site, fault system, and crustal domain scales, allowing high-resolution mapping of long-term stress orientations while preserving local complexity.

Results show dominant, near-pure extensional kinematics with minor local oblique or strike-slip components. The minimum principal stress axes (σ_3) exhibit radial patterns along major bent faults and outward-convex arcs in the Central-Northern Apennines and the Southern Apennine–Calabrian ridge. These stress arcs flank two thinned crustal domains: the Tuscan–Northern Tyrrhenian and the Southern Tyrrhenian regions.

While the stress regime remains consistently extensional along the belt, stress ratio (φ) values exhibit a north-to-south transition from uniaxial tension (prolate ellipsoid) to radial tension (oblate ellipsoid). This gradient is likely controlled by crustal thickness and composition variations, topographic elevation, heat flow, and/or inherited structural anisotropies.

Finally, we integrate stress inversion results with geodetic and seismological datasets using a hybrid gridded model of tensional directions. This cross-disciplinary synthesis validates the geological stress field and provides new insight into seismogenic processes and transient phenomena not always captured in seismic records.

Faults, earthquakes and mechanical stratigraphy of the upper crust: reflections from the seismic sequences of Central Italy

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Keywords: seismogenic faults, rock mechanics, Central Italy.

In a region of complex and recent tectonic activity, the uppermost crust, mainly consisting of sedimentary (or low-grade metamorphic) rocks, is characterized by a high grade of lateral and vertical lithological inhomogeneity, strongly affecting its rheology and mechanical behaviour. In the Umbria-Marche region, the well-known stratigraphy of the upper crust schematically consists of four main lithological groups, with markedly different mechanical properties, object of both lab and filed studies at different scales. They are, top to bottom: Neogene turbidites (alternated sandstones and marls), Jurassic-Paleogene carbonates (massive and well layered limestones), Triassic evaporites (alternated anhydrites and limestones), "phyllitic" basement (sedimentary and/or meta-sedimentary clastic rocks). The thickness of this succession shows strong lateral variations, also due to its involvement in the Apennines fold-and-thrust belt. The active and seismogenic normal faults of the region dissect this complex tectono-sedimentary assemblage.

Most of the seismicity occurs along a set of NNW-SSE trending belts, following the alignment of the major active normal faults of the area and of the Quaternary extensional basins, and orthogonal to the regional direction of extension, as defined by both focal mechanisms and geodetic data. Within this relatively homogeneous and continuous seismic region, we can distinguish (at least) two geological provinces: a NW province (Umbria pre-Apennines), where a 2 km thick turbidites layer covers the carbonates and the top basement is relatively shallow (less than 6 km); and a SE province (Umbria-Marche Ridge), where Jurassic-Paleogene carbonates crop out at the surface, and the top basement is 8 to 12km deep.

In the last 50 years, three major seismic sequences, with mainshocks 5.95 occurred in 1984. However, five seismic sequences occurred from 2010 to 2023: Pietralunga 2010 (Mw = 3.6), Città di Castello 2013 (Mw = 3.6), Gubbio 2021 (Mw = 3.9), Umbertide 2023 (Mw = 4.5).

Both major and minor seismic sequences provide a unique collection of good quality seismological data, registered by increasingly denser instrumental networks and improved by modern localization and processing technologies. The availability in the same area of a substantial amount of geological and geophysical data, constraining the stratigraphic and structural setting of the upper crust, till a depth of 10-12 km, has given the opportunity of an effective comparison between the seismicity distribution and the mechanical stratigraphy of the upper crust. shedding new light on the thickness and depth of the seismogenic layer and contributing to the evaluation of the seismic hazard.

ITHACA 2.0, the updated "ITaly HAzard from CApable faults" Catalogue

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Keywords: ITHACA, capable faults, Quaternary faults.

The ITaly HAzard from CApable faults (ITHACA) Catalogue provides detailed information on capable faults affecting Italian territory. Capable faults are those faults capable to generate permanent surface and/or near-surface deformation during moderate to strong seismic events (e.g., IAEA, 2015, 2022). The Catalogue also includes Quaternary faults whose potential capability still needs to be confirmed or ruled out through specific paleoseismological investigations. Accurate knowledge of the location and characteristics of capable faults is essential for seismic risk mitigation and for the siting and safety of critical infrastructure. This principle guided the initial development of the Catalogue in the 1990s, drawing on scientific knowledge gathered through siting studies for chemical and nuclear power plants and oil and gas pipelines. The Catalogue's first release dates back to 2000. A continuous process of updates that remains ongoing, with the release of progressively refined versions, leaded to the current version: (https://sinacloud.isprambiente.it/portal/apps/webappviewer/index.html?id=068ab01758ee44719b7001b32177c6ea). The ITHACA 2.0 release results from a thorough revision and improvement of the Catalogue, including an analysis of its content based on the current seismotectonic framework, updates to its attributes and spatial localization, and the addition of new records. We based this work on a careful collection and review of the most recent scientific literature, as well as thematic maps and data from technical studies promoted by national and regional authorities. Both existing and new elements have been revised or incorporated based on the information collected from the geological sketches and maps and subsequently compared with those in the Geological Map of Italy, as well as with the morphological features identifiable on digital terrain models at various resolutions. For each fault, we added and populated a new specific field (FaultTraceReference), indicating the specific source we used for fault trace mapping. Additionally, we reorganized the fault elements into structural systems, ensuring consistency with those already recognized in the literature or newly identified based on the local tectonic setting. The new version of ITHACA provides updates for the entire Italian territory, with the exception of limited areas of Tuscany, Lazio, Marche, Umbria and Abruzzo, where the revision is still ongoing. We consider however the fault dataset in these areas consistent with the current state of the literature, incorporating post-seismic studies from 1997, 2009, and 2016 seismic sequences. We completed this 2025 2.0 version with the compilation of a summary technical report, which describes the geological and structural setting and the seismotectonic framework at a regional scale, as well as each fault system and individual structural element identified. A further version of ITHACA will be released after the ending of the PNRR GeoSciences project.

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Unveiling the seismotectonics of the Siena Basin: Insights from the February 2023 and February 2025, M_{max} 3.7 earthquake swarms

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Keywords: seismotectonics, inner Northern Apennines, Siena Basin.

This presentation aims to provide a novel interpretation of the seismotectonic setting of the area surrounding the city of Siena, located in the inner Northern Apennines of southern Tuscany. The analysis is based on recent seismic sequences, historical earthquake records, and geological and structural data. Through history, our study area experienced several moderate earthquakes, the most significant being the 1558 Valdarno superiore, M_w 6.0 event (CPTI15; Rovida et al., 2022). According to DBMI15 (Locati et al., 2022), the city of Siena itself was shaken six times with maximum intensity of VII MCS. In February 2023 and February 2025, the same area was affected by two low-magnitude (M_{wmax} 3.7), upper crustal (4-12 km depth) seismic sequences. Despite their limited moment release, these swarms triggered widespread alarm among the local population over several days. The crustal volume that generated these earthquakes lies amidst a region of the inner Northern Apennines characterized by a thinned crust, high heat flow, and an extensional tectonic regime active since the Miocene. The city of Siena itself is located inside a NNW–SSE, Neogene structural depression (the Siena Basin) that developed through polyphase extensional tectonics and is filled with Upper Miocene to Piacenzian continental and marine deposits. The recent seismic swarms of 2023 and 2025 occurred near the western end of a major transverse crustal structure, approximately trending SW–NE, known in the literature as the *Arbia–Val Marecchia tectonic lineament*. It consists of a broad shear zone composed of several anastomosing fault segments. Some of these faults are seen to cut the surface, displacing Late Pleistocene–Holocene fluvial terraces, controlling the local drainage pattern, and facilitating the ascent of geothermal fluids (Brogi et al., 2014). This hypothesis is supported by the alignment of thermal springs, localised travertine deposits and gas emissions (primarily CO_2 and H_2S). The spatial distribution of the many earthquakes listed in INGV's ISIDe earthquake catalogue roughly follows this structure, supporting its interpretation as an active fault system, at least along some of its segments. The 2023 and 2025 sequences occurred slightly to the north of and along this lineament, respectively, and exhibit right-lateral transtensional motion along a N78-oriented nodal plane, and NW-SE and NE-SW subhorizontal P and T axes. Finally, to improve the spatial resolution of the INGV national seismic network we installed a temporary station at a strategic location of the study area. Our study involved a comprehensive reassessment of structural and kinematic geological data from both surface and subsurface faults surrounding the city of Siena, integrated with i) precisely relocated earthquakes, ii) a revision of event timing, and iii) an updated interpretation of the focal mechanism of the main earthquakes of both sequences.

Brogi A. et al. (2014) - Late Quaternary tectonics in the inner Northern Apennines (Siena Basin, southern Tuscany, Italy) and their seismotectonic implication. J. Geodyn., 76, 25-45, https://doi.org/10.1016/j.jog.2014.03.001.

Locati M. et al. (2022) - Database Macrosismico Italiano (DBMI15), versione 4.0 [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV), https://doi.org/10.13127/dbmi/dbmi15.4.

Rovida A. et al. (2022) - Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 4.0 [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV), https://doi.org/10.13127/cpti/cpti15.4.

The 1997 Umbria-Marche seismic sequence in light of updated geometric-kinematic geological sections: a new starting point for a refresh of the Central Apennines (Italy) seismotectonics

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Keywords: seismotectonics, Central Italy, Umbria-Marche.

Multiple seismic sequences — including the 1997 Umbria-Marche, 2009 L'Aquila, and 2016–2017 Amatrice-Visso-Norcia — have significantly impacted the Central Apennines in Italy, a region shaped primarily by post-orogenic extensional tectonics.

Recent research highlights the reactivation of inherited tectonic structures, such as large thrust faults or earlier normal faults, with a minor formation of entirely new discontinuities. Notably, during the Miocene-Pliocene compressional phase, these pre-existing normal faults were vertically and horizontally displaced, fragmenting the upper crust into compartments. In the following Plio-Quaternary extensional regime, only the well-oriented faults were likely to be reactivated.

This study examines the 1997 Umbria-Marche seismic sequence, which included six mainshocks with magnitudes between Mw 5.0 and 6.0 at depths of 5–8 km. These events clearly align with surface expressions of NNW-trending normal faults running parallel and adjacent to each other.

Despite decades of analysis, the precise identification of the causative faults for the 1997 events remains an ongoing challenge for geologists and seismologists alike.

To address this, we introduce a new, integrated 3D geological and velocity model for the region, along with a 1-D relocation of the seismic events, built upon reinterpreted high-resolution seismic profiles and well data. Our interpretations are further supported by quantitative geometric-kinematic validation techniques.

Our findings reveal a highly intricate architecture of the shallow crust, shaped by major thrust systems and segmented, inherited faults embedded within different thrust sheets. Interestingly, both mainshocks and aftershocks appear to be concentrated within large rock volumes bounded by these thrusts, rather than along simple fault planes.

This updated and quantitatively validated model provides a critical new framework for re-evaluating the seismotectonic setting of the Central Apennines. It offers robust, data-driven constraints for redefining the seismic hazard scenarios in this complex and seismically active region.

A Multidisciplinary Study on the Quaternary Intermontane Bojano Basin (Central-Southern Apennine, Italy): First Insight from a deep borehole stratigraphy (MOSAICMO Project)

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Keywords: deep borehole, tectonic vs sedimentary subsidence rates.

The Molise-Sannio region, in the axial portion of the Southern Apennines (Italy), is a fold-and-thrust belt where the Late Miocene to Early Pleistocene compressional tectonics has been overprinted by a younger extensional stress regime responsible for a significant degree of seismicity, and which is coexisting with strike-slip faulting to the north-east. Active faults in this area are known to be capable of generating M6+ earthquakes. The goal of the MOSAICMO project (Molise SAnnio Integrated Crustal MOdel) is to develop a comprehensive multiscale crustal model of the Molise-Sannio region by combining seismological, geophysical and geological data, with a specific focus on the Quaternary intramontane Bojano basin. By merging geological, new shallow geophysical and aeromagnetic data, a new deep borehole (core BJ1 hereafter), down to 175 m, was drilled in June 2024 in the depocentre of the Bojano basin. The BJ1 core, together with available chrono-stratigraphical data by literature, aims to calibrate geophysical models, extend back in time the history of basin infilling, assess the role played by the complex right-stepping normal fault system bounding the study basin, knowing that the sediment accumulation and its facies variability, alongside with climate change, are an expression of the long-term fault slip rate variability.

The collected litho-stratigraphy in BJ1 is made of alternated coarse grained sediments (loose gravel and coarse sand) with fine massive clayey and sandy silt intervals down to 139 m where the pre-Quaternary bedrock was reached. From 139 to 175 m the upper Miocene deposits (Late Tortonian) of the Molise Flysch were collected. Moreover, several tephra layers were found along the whole Quaternary succession. They were sampled for detailed tephro-stratigraphical and chronological analyses. In addition, samples for paleomagnetic analyses and low field magnetic susceptibility (AMS) were acquired together with samples for micropaleontological analysis. At the end, an age model will be built by merging 14C radiocarbon dating, tephrochronology, tephrostratigraphy and paleomagnetic data.

Preliminary chrono-stratigraphical results suggest that: i) the absence of important soil development and marsh related deposits together with the lack of poor lacustrine features and palaeontological content (e.g. freshwater molluscs) point to the persistence over time of alluvial-palustrine facies; and ii) a preliminary interpretation asks for a substantial long-term balance between tectonic and sedimentary subsidence rates.

Fault activation energy

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Keywords: earthquake energy, graviquake, elastoquake.

Faults are passive features mobilized by the dissipation of the energy and shear stress accumulated in the crustal volume surrounding them. However, the energy in the volume differs from the tectonic setting, i.e., it is gravitational in extensional tectonic settings, whereas it is elastic in strike-slip and contractional tectonic environments. In extensional settings, below 1 km the horizontal tensile stress is overwhelmed by the confining pressure of the lithostatic load. Therefore, the motion pro-gravity of the crustal volume is provided by the lithostatic load that is the vertical maximum principal stress. The elastic energy is rather accumulated by the maximum horizontal principal stresses, i.e., iso-gravity in transcurrent settings and counter-gravity in contractional tectonic settings. The different relation with the gravitational force in the different tectonic settings generates several relevant differences in the three main tectonic environments. The pro-gravity movements, or graviquakes, determine i) lower energy and lower differential stress to activate faults with respect to the other tectonic settings; ii) lower maximum earthquake magnitude than the other tectonic environments; iii) a larger number of low magnitude earthquakes in extensional settings because the crust moves downward as soon as it can move. This model explains the surface morphological asymmetry of subsided versus uplifted topography in the opposite tectonic settings, the higher b-value of the Gutenberg-Richter and the larger number of background and aftershocks earthquakes in extensional tectonic settings both in the Mediterranean and elsewhere in the world.

Integrated 3D Crustal Model of the Irpinia Earthquake (1980) Epicentral Area: New Seismotectonic and Geological Implications

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Keywords: southern Apennines, subsurface geological modeling, local earthquake tomography.

We present the first integrated three-dimensional (3D) crustal model of the epicentral area of the 1980, Mw 6.9, Irpinia earthquake (southern Italy).

Our model was constructed by jointly interpreting various geophysical and geological data: the CROP-04 deep seismic profile, a dense grid of commercial (both public and confidential) seismic reflection profiles, stratigraphic data from deep exploration wells, and a high-resolution 3D velocity model obtained from a new local earthquake tomography.

Despite numerous seismotectonic studies and detailed analyses, a comprehensive 3D reconstruction of the mid-upper crustal geological architecture was lacking in this region of Southern Italy.

Our integrated model provides new insights into the structural setting of the Neogene fold-and-thrust belt. The use of the 3D geological model derived from subsurface data allows us to interpret variations in tomographic velocities (Vp and Vp/Vs) in relation to rock physical properties and to infer the deep structural setting down to 12 km. The results support a thick-skinned tectonic evolution, consistent with the deformation during Pliocene of the Apulian foreland, involving its deeper Permo-Triassic metasediments and the Paleozoic crystalline basement in the core of the main anticlines.

We highlight how background seismicity is organized at two distinct crustal levels, controlled by pre-existing compressional structures and lithological heterogeneities. Shallow seismicity (< 4–6 km), localized in areas characterized by high Vp/Vs values. Conversely, deep seismicity (9-14 km), concentrates in rock volumes with low Vp/Vs values, interpreted as the crystalline basement of the Apulian structures.

The analysis of commercial seismic data has also allowed for a more precise delineation of the Irpinia Fault, responsible for the 1980 Mw 6.9 earthquake, reinforcing the interpretation of a relatively immature structure with a subtle geological and geophysical expression.

This integrated 3D model offers a new framework for understanding active seismogenic processes and fault tectonics in Southern Italy.

Probabilistic fault displacement hazard in the Mt. Etna region

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Keywords: fault displacement, seismic hazard, Mt. Etna.

Earthquakes in volcanic regions show peculiar characteristics, different from other geodynamic settings. In particular, surface faulting is not uncommon even for low magnitudes and can represent an important source of hazard for the local communities and infrastructure. The Mt. Etna area (Sicily, S Italy) hosts frequent seismicity and the two last surface-rupturing earthquakes occurred in 2002 and 2018 (Tringali et al., 2023). Following the 2018 event, a relocation plan for damaged buildings (Neri & Neri, 2025), amounting to over 30 million €, has been enforced in the affected area.

A comprehensive evaluation of the fault displacement hazard is needed for taking proper decisions when it comes to site selection for buildings and infrastructure; the same reasoning may also apply for defining avoidance zone, i.e., areas where specific measures are forbidden.

A way to assess the hazard due to fault displacement is to adopt a probabilistic approach, which computes the expected frequency of exceedance of a given displacement value. Probabilistic Fault Displacement Hazard Assessment (PFDHA) comprises different components, including the characterization of the seismogenetic source (source geometry, magnitude recurrence) and the adoption of empirical relationships about the conditional probability of slip along the principal fault and the expected displacement along- and across-strike.

Currently, several PFDHA models do exist for crustal earthquakes of different kinematics. However, studies specifically dealing with volcanic regions are lacking: this is the main knowledge gap that we address with this contribution. We selected the Mt. Etna region due to several reasons, such as the good knowledge of the geometry and kinematics of the faults; the availability of seismic catalogues including information on surface rupturing (Azzaro & D'Amico, 2014); the availability of coseismic rupture maps for the 2002 and 2018 earthquakes.

We originally developed the coefficients for the model components related to the probability of surface faulting along the principal fault and to the exceedance probability. The latter term results from two distributions, accounting for the average or maximum displacement as a function of magnitude and the amount of displacement along strike. Finally, we explore the hazard related to distributed faulting, considering the probability and amplitude of displacement as a function of distance from the principal fault.

The preliminary results obtained so far allow to address, for the first time, some of the PFDHA model components for a volcano-tectonic setting. We explore the results in the context of the study area, considering the presence of urban areas close to active faults; the obtained results could be useful for the development of proper land planning measures.

Azzaro R. & D'Amico S. (2014) - Catalogo Macrosismico dei Terremoti Etnei (CMTE) Istituto Nazionale di Geofisica e Vulcanologia (INGV), https://doi.org/10.13127/cmte.

Neri M. & Neri E. (2025) - Etna 2018 earthquake: rebuild or relocate? Applying geoethical principles to natural disaster recovery planning. Journal of Geoethics and Social Geosciences, 2, 1-28, https://doi.org/10.13127/jgsg-49.

Tringali G. et al. (2023) - Fault rupture and aseismic creep accompanying the December 26, 2018, Mw 4.9 Fleri earthquake (Mt. Etna, Italy): Factors affecting the surface faulting in a volcano-tectonic environment. Quaternary International, 651, 25-41.

Assessing the feasibility of DInSAR for detecting coseismic deformation in small-magnitude earthquakes: a case study of the 2023 Mw 4.4 Umbertide earthquake (central Italy)

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Keywords: remote sensing, structural geology, earthquake.

Differential Interferometric Synthetic Aperture Radar (DInSAR) has proven to be a valuable tool for detecting ground deformation associated with seismic events. While large earthquakes generate significant surface displacements that are easily captured by satellite-based radar systems, the ability to detect coseismic deformation for smaller events (Mw < 5.0) remains a challenge due to the subtle nature of the ground movement and the influence of atmospheric noise. However, recent advances in satellite imaging technology, such as the high temporal resolution of Sentinel-1 data, have demonstrated the potential for identifying even weak coseismic signals.

This study investigates the potential of DInSAR to detect the coseismic deformation associated with the Mw 4.4 Umbertide earthquake occurred in central Italy in 2023. The focal mechanism of the mainshock indicates an extensional tectonic setting, with a SW–NE oriented T-axis, consistent with the regional stress and in agreement with the focal mechanisms of larger historical earthquakes in Central Italy (e.g., 1997–1998, 2009, 2016–2017).

Sentinel-1 SLC data were processed with the open-source Python tool Snap2DQuake (Occhipinti et al., 2023) and stacking method. The DInSAR analysis produced displacement maps for both the vertical and horizontal (E–W) components, revealing localized deformation with a maximum vertical displacement of 3 cm, consistent with GPS data from the near-fault TABOO observatory. In addition, time series derived using the Small BAseline Subset (SBAS) approach were analyzed to investigate the interseismic phase and potential preparatory processes.

The area of maximum vertical deformation, spanning approximately 7 km², coincides with the epicentral region of the Mw 4.4 mainshock and its associated aftershocks.. The size and geometry of the subsided area are consistent with the downward displacement of the hanging-wall block along a relatively small NE-dipping normal fault, as also suggested by the alignment of hypocenters projected in section and constrained by the interpretation of seismic reflection profiles crossing the epicentral area.

Despite its relatively low magnitude, this event presents an opportunity to assess the lower detection limits of current satellite SAR techniques in a tectonically active region. The study demonstrates that DInSAR can resolve subtle ground movements associated with low-magnitude seismic events and provide insights into the seismogenic structures involved, improving our understanding of crustal deformation processes in seismically active regions.

Occhipinti M. et al. (2023) - Implementing the European Space Agency's SentiNel Application Platform's Open-Source Python Module for Differential Synthetic Aperture Radar Interferometry Coseismic Ground Deformation from Sentinel-1 Data. Remote Sensing, 16(1), 48, https://doi.org/10.3390/rs16010048.

Kinematic Block Modeling approach to estimate the seismic potential of the Northern Apennines external Arc in Emilia Romagna region, (northern Italy)

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Keywords: block modeling, Emilia Romagna, active tectonic.

The Po Plain, in Emilia-Romagna region, hosts part of the outermost sector of the Northern Apennines orogenic front. The low strain rate and the compressional velocity gradient acting in these areas are well documented through recent studies (Serpelloni et al., 2022), although which fault segment plays the dominant role in accommodating the recognized deformation, during the interseismic period, is still unknown. A part of this strain was released during the 20 and 29 May 2012, Mw 6.1 – 6, Emilia-Romagna seismic crisis, which several authors ascribed to ruptures along the Mirandola fault and part of the Ferrara Romagna faults system. In this complex tectonic context, we propose a comprehensive kinematic block modeling approach (McCaffrey, 2002; Meade & Loveless, 2009) by exploiting all the available faults parameters, locking depth and geodetic data, to identify which fault segment effectively accommodates the compressive velocity pattern by uniform slip rates in the long term. Our solution shows that the modelled external front variably reproduces the observed velocity gradient by a predominant dip slip rate component of ~ 2 mm/yr and a subordinate strike slip rate component of ~ 1 mm/yr. We therefore discretised the proposed faults model by means of a triangular dislocation elements 3d mesh, to estimate the deficit of the slip rate (Savage,1983). This step of modeling allowed us to discriminate possible locked asperities, characterized by a high interseismic coupling coefficient, from areas affected by aseismic behaviour defined by a low interseismic coupling coefficient. We furthermore computed the area of the detected coupled fault portions to propose a set of possible rupture scenarios and estimate the amount of the interseismic moment rate that the Emilia-Romagna region is actually accumulating. The obtained seismic moment accumulation rate is equal to 4.1 e16 Nm/yr, during the last ~ 35 years. Assuming that all this energy is released elastically, it would be the equivalent of a Mw 4.49 earthquake, each year.

Mccaffrey R. (2002) - Crustal block rotations and plate coupling. Plate Boundary Zone, 101-122.

Meade B.J. & Loveless J.P. (2009) - Block Modeling with Connected Fault-Network Geometries and a Linear Elastic Coupling Estimator in Spherical Coordinates. Bulletin of the Seismological Society of America, 99(6), 3124-39, https://doi.org/10.1785/0120090088.

Savage J.C. (1983) - A Dislocation Model of Strain Accumulation and Release at a Subduction Zone. Journal of Geophysical Research, 88(B6), 4984-96, https://doi.org/10.1029/JB088iB06p04984.

Serpelloni E. et al. (2022) - Surface Velocities and Strain-Rates in the Euro-Mediterranean Region From Massive GPS Data Processing. Frontiers in Earth Science, 10, https://doi.org/10.3389/feart.2022.907897.

Unveiling a blind, active fault structure in Southern Piedmont region (North-West Italy) via the new tool TESLA for micro-seismicity analysis

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Keywords: seismotectonics, focal mechanisms, TESLA.

Analysis of earthquake source mechanism is crucial for seismotectonic studies, but it is often limited by traditional methods plagued by issues of precision and automation. This is particularly true for deep and complex seismogenic structures, as it is the case for Southern Piedmont.

In this study, we present a detailed application of TESLA (Tool for automatic Earthquake low-frequency Spectral Level estimAtion; Adinolfi et al., 2023), a novel tool designed to overcome these limitations. TESLA automates the calculation of low-frequency spectral levels of P and S waves, integrating this data with P-wave polarities to significantly enhance the accuracy of focal mechanisms and seismic moment estimations. Its ability to automatically identify the optimal signal window reduces human intervention and increases efficiency, providing more reliable results.

We demonstrate TESLA's effectiveness in refining source mechanism analysis by applying it to seismic activity near Asti (AT), in Southern Piedmont. Our analysis reveals that the observed cluster consists of two distinct seismic sequences, occurring in 1991 and 2012, which activated the same fault structure. By examining a total of 36 events with magnitudes ranging from 1.1 to 3.7, we provide high-resolution insights to the spatial dimension and geometry of this fault structure.

We show how conventional analyses on regional-scale seismic data lack the resolution needed for precise identification and characterization of seismogenic sources. Advances to the understanding of this complex tectonic area and its associated seismic hazard, needs the coupling of high-quality, and up-to-date seismic catalogues with accurate focal mechanism solutions derived via innovative tools such as TESLA.

Adinolfi G.M. et al. (2023) - TESLA, A Tool for Automatic Earthquake Low-Frequency Spectral Level Estimation: The Study of 2013 St. Gallen Earthquake Fault-Plane Solutions. Seismological Research Letters, 94(5), 2441-2455, https://doi.org/10.1785/0220230033.

Mapping fault architecture from depth to surface: integrating microseismicity and structural geology in low-strain Apennine regions

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Keywords: structural geology, microseismicity, 3D fault model building.

High-resolution microearthquake data provide a powerful window into active fault architecture from depth to surface in slowly deforming regions with sparse instrumental seismicity. We integrate microseismic clusters derived from enhanced catalogs with detailed structural mapping to reconstruct the three-dimensional geometry of some seismogenic extensional faults in the Latium-Abruzzi sector of central Italy. Investigated earthquake clusters align geometrically and kinematically with newly mapped or extended normal faults, which show evidence of Late Quaternary activity. The built 3D model depicts a set of SSW-dipping, high-angle curvilinear faults (Sora, San Donato Val di Comino, Villavallelonga, and Pescasseroli) whose cut-off depths deepen NNE-ward, from ~6 to ~14 km, and appear to sole into a basal detachment with an average dip-angle of 30-35°. The microseismic patches localized at the roots of the high-angle faults extend along the fault dip rather than the strike. This unusual configuration suggests a stress release pattern governed by iso-oriented anisotropic roughness and corrugations on the detachment, capable of localizing upward fluid migration and earthquake triggering along the hangingwall splays. Stress inversion indicates a persistent NE–SW tensional stress field consistent across geological and instrumental timescales. Empirical magnitude-area scale, accounting for both epistemic uncertainty among scaling laws and areal variability of the considered fault surface, indicates a range of maximum magnitudes between 6.0 and 6.5, coherent with the regional seismotectonic context. Our findings provide new constraints on fault connectivity, stress distribution, and fluid-fault interactions, contributing to identifying seismogenic sources that might have remained unknown considering geological and seismic data in isolation.

The INGV contribution to the SPIN project: Test delle buone pratiche per lo Studio della Potenziale INterazione tra attività offshore e pericolosità naturali

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Keywords: 3D geological/geophysical model, seismic shaking scenarios, seismic hazard assessment.

The Italian National Institute of Geophysics and Volcanology (INGV) has been actively involved in developing advanced 3D geological and geophysical models to support seismic hazard assessment across the Italian territory. In this context, the SPIN project (*Test delle buone pratiche per lo Studio della Potenziale INterazione tra attività offshore e pericolosità naturali* - Best practice testing for the Study of Potential INteractions between offshore activities and natural hazards) was launched, involving several institutions, including INGV.

The workflow adopted by the INGV team combines the interpretation of 2D and 3D seismic reflection profiles, deep well data, geological and structural maps, technical reports, and available crustal models to build high-resolution 3D geological and velocity models extending down to ~50 km depth. This integration enables the accurate reconstruction of the geometry and kinematics of major tectonic structures, providing a solid geological basis for seismotectonic analyses.

In this framework, two key focus areas have been investigated over the last few years: the northern Adriatic Basin, encompassing the Marche offshore and adjacent onshore regions, and the tectonically complex domains of Sicily, including the Apennine-Maghrebian thrust belt, the Catania-Gela foredeep, and the Hyblean Plateau foreland. These regions, characterized by active tectonics, recent seismicity, and extensive subsurface datasets, offer ideal settings to apply and validate integrated seismotectonic modeling approaches. As a result, regional-scale models, covering areas of approximately 18,000 and 19,000 km² have been developed.

Based on these 3D models, seismic shaking scenarios have been generated, driven by the seismogenic structures identified in each area. This can be achieved using both classical methods, such as ShakeMaps with synthetic faults, and advanced hybrid numerical methods for broadband seismic wave simulations within three-dimensional crustal models. The development of robust geological and velocity frameworks at crustal scale is thus crucial for improving the reliability of wave propagation models and, ultimately, for refining seismic hazard assessments.

Overall, this approach highlights how multidisciplinary 3D modeling represents a fundamental advancement for the characterization of fault systems and the evaluation of seismic risks in Italy, providing essential tools for more accurate and realistic seismic scenario simulations at both regional and local scales.

Hunting capable faults: 3D Deep Resistivity Modeling of the Pantano di San Gregorio Magno basin, Southern Italy

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Keywords: active and capable faults, deep resistivity tomography, geophysical imaging.

The identification and characterization of active and capable faults play a crucial role in subsurface modelling, especially for improving seismic hazard assessment in areas with infrastructure development, thereby mitigating the impact of potential earthquakes. This study presents the preliminary results of a 3D deep resistivity acquisition in Pantano di San Gregorio Magno, in Southern Italy. This region has been affected by surface ruptures across the Monte Marzano Fault System. Surface ruptures occurred during the largest earthquakes of the last century in the Southern Apennines (i.e., the 1980, Ms 6.9, Irpinia earthquake, Westaway & Jackson, 1987).

This investigation aims to detect fault segments affecting both the substratum and the sediments infilling the Pantano di San Gregorio Magno intramountain basin. In this regard, the geophysical target was set to a depth range between 25 and 250 meters. The survey was conducted using the FullWaver System (IRIS® Instruments) and represents the first geophysical survey to fully cover the Pantano di San Gregorio Magno basin. The instrumentation consists of a series of wireless dual-channel digital receivers and a 5-kW time-domain induced-polarization transmitter (Sapia et al., 2021), which allow us to overcome morphological and logistical limitations. After a thorough quality check and filtering of the acquired data, a robust inversion was performed using ViewLab software, leading to a comprehensive 3D resistivity model of the investigated basin. The processed data permitted a detailed characterization of the entire basin structure, leading to the identification of fault segments buried by Quaternary sediments and providing additional insights consistent with interpretations previously proposed by Bruno et al. (2024).

This study demonstrates the effectiveness of deep resistivity tomography using wireless acquisition systems in identifying fault segments in intramountain basins developed in carbonate bedrock (a resistive medium) and infilled with silts and clays (conductive media).

Bruno P.P.G. et al. (2024) - Multidisciplinary high resolution Geophysical Imaging of Pantano Ripa Rossa Segment of the Irpinia Fault (Southern Italy). Nature, Sci. Rep., 14, 26891, https://doi.org/10.1038/s41598-024-75276-6.

Sapia V. et al. (2021) - 3-D deep electrical resistivity tomography of the major basin related to the 2016 M_W 6.5 Central Italy Earthquake Fault. Tectonics, 40, e2020TC006628, https://doi.org/10.1029/2020TC006628.

Westway R. & Jackson J. (1987) - The earthquake of 1980 November 23 in Campania-Basilicata (southern Italy). Geophysical Journal International, 90(2), https://doi.org/10.1111/j.1365-246X.1987.tb00733.x.

3D Structure of the Central-Southern Apennines Transition: Implications for Seismotectonics in the Matese-Sannio region

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Keywords: Southern Apennines, geological modeling, active tectonics.

The Matese-Sannio region in Southern Italy, straddling the transition between the Central and Southern Apennines, offers a unique natural laboratory to investigate the complex interplay between major tectonic structures and seismic activity. This area is not only key to understanding the orogenic evolution of the Apennines but also hosts the epicenters of large (M 6+) historical earthquakes, underscoring its present-day seismotectonic importance.

This contribution presents insights from the multidisciplinary MOSAICMO project, which integrates regional-scale structural analysis with detailed investigations of the Quaternary Bojano intramontane basin and comprehensive seismological and geophysical analyses. We focus on the 3D subsurface reconstruction of the Matese-Sannio region down to approximately 10 km depth, utilizing a dense grid of seismic reflection profiles constrained by well-log data. This reconstruction provides a detailed geometric framework of the major tectonic structures in this seismically active zone.

To assess the kinematic evolution and reliability of our structural interpretation, we have performed kinematic forward modeling, providing independent constraints on the geometry and timing of deformation. Furthermore, we compare our findings with existing paleogeographic reconstructions from literature to elucidate the complex interactions between different paleogeographic domains involved in the orogenic processes within this focused area. We also compared our findings with the distribution of the instrumental seismicity in the area.

Our results deliver an updated and detailed picture of the present-day structural architecture at the critical transition between the Central and Southern Apennines. This refined structural framework serves as a fundamental basis for understanding the geological context and behavior of seismogenic faults within the region and will underpin more detailed seismotectonic analyses within the broader MOSAICMO project. By integrating subsurface imaging with kinematic modeling, this study contributes to a more comprehensive understanding of the structural controls on potential future seismic events in this tectonically active part of Southern Italy.

Geological data to define the presence of active and capable faults in urbanised areas of the central Apennines

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Keywords: surface faulting seismic microzonation central Apennines.

Active and capable faulting is the result of the ongoing extensional tectonic regime in the central Apennine chain. Seismic microzonation is a tool for managing this critical issue, aimed to plan actions for mitigating the risk of ground surface displacement. We here analyse two case studies in the municipalities of Rocca di Mezzo and Castel di Ieri, located a few tens km S and SE of the town of L'Aquila. Our aim is to assess potential surface displacement associated with normal faulting through detailed analysis along the traces of known and presumed capable fault branches. Rocca di Mezzo is located on the Altopiano delle Rocche. A presumed active normal fault is hypothesized in the western portion of the village, based on borehole data suggesting a possible abrupt depth variation in the carbonate bedrock, supposed to be caused by recent normal fault displacements. Given the proximity (just a few km in plain view) to the Ovindoli-Piani di Pezza active fault system (Pantosti et al., 1996), this supposed fault would represent a further splay of the main structure. To verify the actual existence of this fault branch, we performed detailed geological investigations. Field analyses revealed no evidence of extensional faulting in the area where the fault branch is hypothesised. Shear planes affecting pre-Quaternary limestone bedrock were associated only with reverse faulting, attributed to the compressive tectonic phase currently inactive. Moreover, borehole data and field observations allowed the reconstruction of the geometry of the interface between Quaternary deposits and the underlying carbonate bedrock, revealing a gradual general deepening of the carbonate substratum, as resulting solely from just the bedrock attitude. Moreover, a trench excavated across the trace of the supposed fault revealed a late Holocene lacustrine sequence which is not displaced by any fault plane. The village of Castel di Ieri, located in the Subequana Valley, is affected by a segment of the Middle Aterno Valley-Subequana Valley active fault system (Falcucci et al., 2011). However, the trace of the fault within the village has not been defined at the scale suitable for seismic microzonation studies. Detailed geological surveys allowed to identify a complex 70 m-wide fault zone within the village, comprising at least four fault splays. We performed a trench in the village intercepting a fault plane that affects Early Pleistocene lacustrine deposits. A second fault splay was identified a few meters to the east, placing the carbonate bedrock in contact with the same lacustrine sequence. Further splays are defined by the presence of aligned shear planes affecting both the bedrock and the Early Pleistocene lake deposits. As a whole, these case studies underscore the complexities of identifying faults in urbanised areas and highlight the importance of acquiring robust geological field evidence before hypothesising the presence of an active and capable fault.

Falcucci E. et al. (2011) - The 2009 L'Aquila earthquake (Italy): what next in the region? Hints from stress diffusion analysis and normal fault activity. Earth Planet. Sci. Lett., 305, 350-358, https://doi.org/10.1016/j.epsl.2011.03.016.

Pantosti D. et al. (1996) - Paleoseismicity of the Ovindoli-Pezza fault, central Apennines, Italy: a history including a large, previously unrecorded earthquake in the Middle Ages (860-1300 A.D.). J. Geophys. Res., 101, 5937-5959, https://doi.org/10.1029/95JB03213.

Geological and geophysical survey to characterise earthquake surface deformations: examples from southern Patagonia (Argentina)

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Keywords: earthquakes, ground deformations, Patagonia.

Earthquakes can trigger widespread effects on land due to their strong ground shaking, and the resulting effects can be found over wide areas, providing a clue to the recurrence pattern of major earthquakes. On 13th October 2021, a Mw = 5.5 earthquake occurred near El Calafate (Argentina), southern Patagonia, in the frontal part of the Andean fold-and-thrust belt, at a depth of 10 km (Inpres, 2021). In this portion of the foreland, a thick-stick tectonic style characterises the metamorphic basement, and the overlying sedimentary cover pertains to the Upper Cretaceous- Neogene Austral-Magallanes basin (Nullo et al., 2006). The moment tensor solution indicates thrust faulting with planes dipping respectively WSW 41° and ESE 60°. Several aftershocks struck the area, with the largest of October 27th reaching Mw 3.1. The area is affected by sporadic shallow crustal seismicity with few events > Mw3 occurred in the last decades (Correa-Otto & Gianni, 2023).

The epicentral area is located 20 km west of the town of El Calafate, where the Rio Centinelle enters the southern shore of Lago Argentino with a large delta. Damage reports include a few ground deformations along the road embankment and landslides from surrounding reliefs.

The ALOS-2 interferogram shows a few tiny significant phase discontinuities over the epicentral area due to the moderate magnitude and probably by shallow tectonic faulting rupture. The analysis of the ground deformation in the InSAR indicates few lobes separated mainly by NE-SW and subordinate N-S alignments. A subsequent field-based geological, morphostructural and remote sensing techniques post-earthquake survey permitted data collection related to the ground deformations, including rockfalls and rockslides. Rockfalls of many hundreds of cubic meters in highly jointed rock mass have been identified along lineaments corresponding to the main fault zones. In the southern shore of the Lago Argentino, poorly consolidated and laminated Pleistocene lacustrine deposits outcrop along a few-meter-high cliff (Lozano et al., 2020). The decimeter-thick sands show soft-sediment deformation associated with liquefaction structures, suggesting that the area has also been affected by historical seismicity.

A geophysical survey in the epicentral area, with a sub-bottom profile in the Lago Argentino, shows displacement of the lake floor along the active fault.

The spatial distribution of the examined ground ruptures resulted in excellent agreement with respect to the epicentre area of the main shock.

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Seismotectonic Framework of the Northern Apennines: Insights from new focal mechanism analysis along the Livorno-Pistoia-Monghidoro alignment

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Keywords: earthquake, focal mechanism, Northern Apennines.

The seismology of the northern Apennines reveals a complex and depth-dependent tectonic regime, as evidenced by the analysis of focal mechanisms from approximately 40 earthquakes with magnitudes below 5.0 that occurred over the past twenty years along the Livorno–Pistoia–Monghidoro alignment. This dataset highlights the presence of two distinct crustal levels, each characterized by different deformation styles.

In the upper crust, for events with hypocentral depths shallower than 20 km, the dominant tectonic regime is extensional. The focal mechanisms show normal faulting consistent with NW–SE trending Apenninic structures, which are also responsible for the formation and ongoing development of intramontane basins. This extensional deformation reflects the active crustal thinning processes affecting the axial zone of the Northern Apennines.

In contrast, seismic events with hypocenters deeper than 20 km display focal mechanisms indicative of a left-lateral (sinistral) strike-slip regime, often with a transpressional or transtensional component. These deeper earthquakes are not associated with surface faulting evidence but are likely related to the regional dislocation of major tectonic units within the orogenic crust. In particular, the spatial distribution and kinematics of these events correlate well with the more internally located position of tectonic fronts north of the Livorno–Pistoia–Monghidoro line, suggesting differential motion and internal deformation between major crustal blocks.

Overall, this dual seismic behavior highlights the structural complexity of the Northern Apennines [e.g. 1, 2] and emphasizes the role of inherited crustal architecture and deep-seated tectonic boundaries in controlling seismic activity at different crustal levels.

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Airborne LiDAR survey for Monte Orsello Fault structural analysis

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Keywords: airborne LIDAR, fault structure analysis, Monte Orsello Fault.

High-resolution airborne LiDAR (Light Detection And Ranging) products may enable precise fault scarps morphometry in active tectonic regions. In this work, we present the geomorphometric and structural analysis of the NW-SE-trending Monte Orsello Fault (MOF), one of the principal segments controlling the Campo Felice Basin in the Central Apennines of Italy. The study employs a High-Resolution Digital Elevation Model (HR-DEM) derived from the airborne LiDAR data, processed through ESRI ArcGIS Pro software, to extract key morpho-structural features and support detailed mapping of the fault system.

The integrated workflow, combining HR-DEM products with high-precision field data, allowed the identification of surface fault traces, scarp geometry, and geomorphic markers. It based on approaches successfully applied to similar Apennine fault systems (Pucci et al., 2021). Moreover, through this methodology we aimed to quantify post-Last Glacial Maximum (LGM) fault throws and to investigate geometric complexity of the MOF which are critical for understanding regional tectonic evolution and seismic hazard (Schirripa Spagnolo et al., 2021).

This research demonstrates how integrated geomorphometric techniques and high-resolution remote sensing data can enhance fault scarp characterization and tectonic mapping in complex terrains, contributing new insights into the seismotectonic framework of the Campo Felice Basin (Benedetti et al., 2013).

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Unveiling seismogenic structures and fluid reservoirs via scattering and absorption imaging

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Keywords: attenuation imaging, fluids, crustal structure.

The study of novel crustal imaging techniques has been significantly expanded and diversified in recent years. The increasing application of various imaging methods, often integrated within the same region or using comparable datasets, has progressively enhanced our understanding of crustal properties, frequently complementing geological and structural analyses in areas of interest. Seismic scattering and absorption imaging have demonstrated high sensitivity to crustal rheology and the presence of faults or fractures (scattering), as well as to the presence of fluids, elevated temperatures, and partial melt (absorption). Several applications have already been carried out in tectonic, volcanic, and geothermal settings across various regions of the world, revealing good correlation with independently available geological and geophysical information.

In this study, we apply peak delay and Q-coda method, implemented in the open access code MuRAT (version 3.0), to map scattering and absorption imaging of two geologically significant and geographically proximate areas in southern Italy: 1) the largest onshore oilfield in Europe, the High Agri Valley (HAV, in Basilicata region) and 2) one of the widest seismic gap in Italy, the Mt. Pollino area (at the boundary between Calabria and Basilicata regions). In both areas, low-frequency scattering anomalies well correlates with large fault systems and marks the main structural barriers for seismicity. Fluids trapped within the Inner Apulian Platforms and the tectonic barriers have been highlighted by high-absorption anomalies, corroborated by high Vp/Vs and other geological and geophysical information. In the HAV, the reinjection of wastewater into the Costa Molina 2 well (in the HAV) serves as a benchmark for fluid absorption sensitivity, revealing high-absorption anomaly exactly at the depth where the well opens and fluids are reinjected (around 3000 m b.s.l), which also correlates with induced micro-seismicity. The combined use of these techniques, together with available geological and geophysical information can improve our knowledge of the crustal structure of high hazardous seismogenic volumes.

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Constraining the geometry and kinematics of the Quaternary fault system in the Campania–Lucania Apennines: a multidisciplinary perspective

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Keywords: Southern Apennines, seismic section interpretation, extensional Quaternary faults.

The Campania-Lucania Apennines have long intrigued geoscientists due to their complex stratigraphy and structural architecture, as well as their potential for hydrocarbon accumulation. This region is characterized by recurrent and intense seismic activity, including significant historical and instrumental events, such as the 1980 (Mw 6.9) Irpinia earthquake.

Broad scientific literature suggests that much of this seismicity is extensional in nature, linked to Pleistocene-Holocene normal faults, which dip both eastward and westward and have contributed to the origin of NW-SE oriented continental basins.

In the northeastern sector of the Alburni Mountains, the extensional structural framework is primarily defined by east-dipping normal faults, which represent the surface expression of a regional synthetic detachment plane. This study aims to determine whether this deformation pattern can be extended to encompass the larger internal sector of the Campania-Lucania arc, from the Sele Plain to the Mt. Cervati massif, located a few dozen kilometres to the southwest.

To accomplish this, it is crucial to analyze the geometry of the extensional fault system, the tops of the main tectonic units, the associated syntectonic basins, and the thickness of their infill. Here, a multidisciplinary approach has been employed. Surveys of key areas have provided new data for the preparation of a regional-scale geological-structural map, covering ~9,000 km^2, from the southern flank of the Picentini Mountains to the northwestern border of Mt. Pollino, produced through the reprocessing of published data.

These data serve as the surface constraint for drawing four shallow geological cross-sections. These sections, integrated with the logs of some public calibration wells, supported the interpretation of a grid of 12 seismic lines provided by Eni, as well as a series of additional lines of comparable quality, accessible from the ViDEPI database, which were digitized from document format to SEG-Y format.

Integrating geological field observations with geophysical data allowed the interpretation of the seismic dataset, which was converted to depth. This resulted in a series of crustal sections that enable comparison of both contractional and extensional structures across the entire study area. Additionally, the cross-sections supported restoration analysis, including assessment of elongation along the same transects.

The findings that contribute to the evaluation of the area's structural framework consist of a 3D model created from transects along the converted seismic lines. This model aids in the development of a comprehensive 3D model of active extensional faults in the southern Apennines, as part of the MUSE 4D PRIN project.

An automatic workflow to infer focal mechanisms of microearthquakes: Application to Southern Italy

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Keywords: focal mechanisms, convolutional neural network, Southern Apennines.

Focal mechanisms of microearthquakes are one of the most challenging tasks in seismology even today. Inferring the P-wave polarity of low signal-to-noise ratio earthquakes often depends on the operator's experience. To overcome this limitation, in recent years machine learning techniques have enabled not only event detection but also polarity recognition in complex cases such as low-magnitude events.

In this study, we test the performances of the Convolutional First Motion (CFM) method (Messuti et al., 2023), which adopts a convolutional neural network to retrieve P-wave polarities. The test was performed on a dataset of 16 years of seismicity that occurred in southern Apennines, one of the most seismically hazardous systems in Italy monitored by the Irpinia seismic network ISNet (Weber et al., 2007). To remove any possible bias in the evaluation of the performances of CFM due to the time dependent location procedures of ISNet, as a pre-processing we first relocated all events. Then, we applied CFM and eventually calculated the best double-couple mechanisms that fit the inferred P wave polarities.

The reliability of the entire workflow was assessed through multiple quantitative indicators, including the analysis of focal mechanism self-consistency and the comparison with the regional stress field orientation reported in the literature (De Matteis et al., 2012). We find a positive correlation between the Kagan angle (Kagan, 1991) and the inter-earthquake distance for inter-earthquake distances smaller than about 3-4 Km, with a good consistency of the focal mechanisms of closely located earthquakes. For larger inter-event distances, instead no scaling appears between the inter-earthquake distance and the Kagan angle, which reaches a plateau. The predominant mechanism in the area is a normal faulting, with some tending to strike-slip and rare reverse fault events. The extensional stress field, oriented NE-SW, obtained by inverting the retrieved focal mechanisms, well matches the outcomes of previous studies of the area, and is extremely stable by changing the number and quality of mechanisms. Moreover, we demonstrate that the observed Kagan angle distribution is well fit by a Cauchy distribution of rotation angles between focal mechanisms produced by micro-dislocations. We find that for large inter-event distances, the parameter of the Cauchy distribution indicates a high degree of complexity of the fault system generating the earthquakes, while this parameter decreases to about 0.2 when only closely generated earthquakes are selected, suggesting a rather self-consistent system of faults at short inter-event distances, as expected.

Our results show a strong reliability of the proposed workflow, which would not only enable faster calculation of focal mechanisms but could even be implemented as an additional piece in seismological monitoring.

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Quaternary kinematics of the Adria plate along a transect from the Southern Apennines to the Albanides

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Keywords: Adria plate, geodynamic models, convergence zones.

The Adria plate is deformed and consumed by subduction and collisional processes along the peri-Adriatic mountain belts (Apennines, Dinarides and Hellenides). The PRIN Project AdriaLab aims to unravel the geodynamic processes of the Adria plate by providing a natural laboratory where a geodynamic model of a (double) subduction zone can be tested using geological and geophysical data. In this context, we propose a multidisciplinary study that merges marine geological, seismological and geodetic data along a transect that extends from the southern Apennines-Calabrian Arc to the Dinarides-Hellenides transition (Albanides).

In particular, the crustal architecture and a new scheme for the Quaternary kinematics of the Adria plate will be reconstructed based on the interpretation of seismic reflection profiles (Crop Mare, commercial multi-channel seismic lines from the Videpi database with variable resolution/penetration) coupled with newly collected GNSS measurements and relocalized seismic events. The high-penetration seismic profiles reveal the presence of high-angle transcurrent faults, some of which offset the seafloor and form NNW-trending structural ridges extending southeastward from the Apulia platform. In the area west of Corfù Island, contractional structures deform Miocene units. Geodetic data reveal the ongoing deformation processes between the Adria plate boundaries. We used the velocity solution processed (code vel2020) by the RING network and reoccupied (years 2022 and 2024) 37 benchmarks belonging to the IGM95 network. IGM95 data have been reprocessed using GAMIT-GLOBK software. Velocity fields, referred to as ITRF2014 to the stable part of the Eurasian plate, highlight a convergence pattern between the Dinaric-Albanian and Southern Apennine fronts, oriented approximately NNE. The seismological analysis aims to characterize recent and historical seismicity to improve understanding of the regional seismotectonic framework. We analyze seismic events recorded by the INGV networks over the past 40 years, focusing on hypocentral location, spatiotemporal distribution, and kinematic characteristics. These seismological parameters are integrated with geological and geophysical datasets to assess potential correlations with known or inferred active structures. The multidisciplinary research strategy is expected to disclose unsolved geodynamic issues that apply to other convergence zones, such as the causes and mechanisms of lateral slab tearing and break-off and their effect on orogenic processes.

Seismic behavior of offshore thrusts: the case of the 2022 Mw5.8 Adriatic earthquake

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Keywords: Adriatic Sea, seismogenic buried faults, thrust seismic behavior.

Tectonic setting is a key parameter influencing earthquake rupture dynamics. While this concept has been investigated in extensional and strike-slip settings, its role in compressional environments remains poorly constrained due to limited data availability. To investigate the relationship between tectonic setting and seismic behavior, we analyze the Mw5.8 earthquake of November 9, 2022, which occurred offshore the northern Adriatic Sea, along the outermost front of the Northern Apennines fold-and-thrust belt.

Using a multidisciplinary dataset that includes seismic reflection profiles, well logs, GNSS data, strong-motion records, and historical seismicity, we identify the thrust activated during the earthquake. We document how the structural setting of the fault activated correlates with a low rupture velocity. These observations suggest a direct link between tectonic setting and distinctive seismic behavior.

To place these results in a longer-term context, we assess regional deformation using GNSS data and historical earthquake records. Through the combination of estimated long-term tectonic deformation rates with coseismic slip from the 2022 event, we propose hypotheses on the seismic cycle.

These findings provide new constraints on seismic behavior in compressional tectonic environments. The integrated approach applied here may serve as a transferable workflow for other thrust-dominated offshore regions worldwide.

Late Pleistocene-Holocene tectonic activity of the Longhere-Fadalto-Cadola Line (Lapisina Valley, Vittorio Veneto, NE Italy)

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Keywords: active and capable fault, eastern Southern Alps, NE Italy.

In the framework of the National Project of Seismic Microzonation – Third Level (FAC), we made a paleoseismological study on the eastern segment of the Bassano-Valdobbiadene Thrust, i.e. the left-lateral Longhere-Fadalto-Cadola transpressive fault (Costa et al., 1996). The investigated area lies along the Pliocene-Quaternary front of the Eastern Southern Alps (ESA) in the eastern Venetian Prealps. The formation of the ESA is related to the Neoalpine compressive event that began in the middle Miocene, but the main structural development of the external Chain occurred during the Messinian-Pliocene tectonic phase (Castellarin & Cantelli, 2000), through the emplacement and propagation of the fold-and-thrust system towards the SSE. The most important tectonic structure of the area is the Bassano-Valdobbiadene Thrust *Auct*. It extends SW-NE along the prealpine border of the Veneto region, causing the outcrop of the Jurassic-Cretaceous carbonate units of the Belluno Basin. These units, which form the macro-anticline of the Mt. Cesen-Mt. Visentin ridge, overthrust the Miocene Molasse units to the south-east (Antonelli et al., 1990). Northeastward, along the Lapisina Valley, the Bassano-Valdobbiadene Thrust changes direction to a roughly N-S orientation (Longhere-Fadalto-Cadola Line in Costa et al., 1996) developing on the western margin of the Mesozoic Friulian Carbonate Platform towards the Belluno Basin. In the current stress field, active since Pliocene-Quaternary, the reverse structures of the Veneto prealpine front accommodate the deformation accumulating at rates of 2-3 mm/yr (Serpelloni et al., 2016) in response to a maximum compressional axis oriented approximately N-S. In this region, two historical earthquakes with M≥6 occurred, as reported by the Parametric Catalogue of Italian Earthquakes: the 1873 Alpago seismic event (Imax = X MCS, Mw = 6.3) and the 1936 earthquake that affected the Cansiglio area (Imax = VIII MCS, Mw = 6.1). Both seismic events caused high damage in the area between Vittorio Veneto and Caneva. The Quaternary evolution of this sector was influenced by both dynamics related to the Piave glacier, which occupied the Lapisina Valley during the Last Glacial Maximum (LGM), and large gravitational movements that occurred during the post-glacial phase. In this work, we present the preliminary results of the geophysical and paleoseismological study along the Longhere-Fadalto-Cadola Line: the excavated trenches involved glacial, fluvioglacial, alluvial, lacustrine and slope deposits, LGM and post-LGM in age, and revealed evidence of tectonic deformation confirming the activation of the structure even during the Late Pleistocene-Holocene.

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Recent seismic swarms in Calabria

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Keywords: seismic swarms, Calabrian Arc, seismotectonics.

Seismic swarms and sequences are a common feature of crustal seismicity in the Calabrian Arc (Calderoni et al., 2021; Chiappetta & La Rocca, 2023; La Rocca et al., 2025). Most of these swarms are characterized by low magnitude, irregular and variable number and rate of earthquakes, and hypocenters distributed within a seismogenic volume that is often much larger than expected based on the size of the mainshock. Source kinematics is consistent within a swarm only in certain cases. The depth of swarms recorded in recent decades varies greatly, ranging from just a few kilometers (as in the cases of Mt. Pollino, 2010-2014, and Albi, 2020) to approximately 40 km (such as Catanzaro Lido, 2022). In many instances, the relationship between these swarms and recognized tectonic structures is unclear or entirely unknown. In the first months of 2025 two notable swarms were recorded, one near Scandale (KR) and another near Tiriolo (CZ).

The Scandale seismic swarm began on February 18, 2025, with a few earthquakes of magnitude M <2 .0 occurring between 12:12 and 12:25 UTC. They were followed by a magnitude M3.6 event at 12:40 UTC, located at a depth of approximately 30 km. Seismic activity intensified in the following hours, with nine earthquakes of magnitude M≥3.0, including the mainshock of magnitude M3.8 at 13:11 UTC. Between February 18 and February 28, 2025, a total of 59 earthquakes were recorded within a 7 km radius centered at latitude 39.10°N and longitude 16.95°E. Of these, 9 events had M ≥ 3.0 and 15 had M ≥ 2.0. Most of the seismicity occurred on February 18, with 50 events recorded on that day, while only a few smaller events followed in the subsequent days. The epicentral distribution is narrow and elongated in a NW–SE direction, suggesting the presence of a tectonic structure responsible for the swarm. The Tiriolo seismic swarm began in early March with sporadic, very small earthquakes. Seismic activity increased a lot in number between March 12 and 20, reaching peaks of 130 events per day. Six earthquakes had magnitudes M ≥ 3.0, with the largest reaching M = 3.4. The Gutenberg–Richter magnitude distribution for this swarm is clearly characterized by a b-value greater than 1. Due to the sparse seismic network in the area, earthquakes smaller than M1.0 could not be reliably located. Nevertheless, more than 800 events were located, most of them at depths between 7 and 11 km. The strongest events exhibited normal faulting with NE–SW striking planes.

Detailed analysis of seismic swarms is essential for investigating the seismogenic volume, identifying the faults involved in swarm generation, understanding their kinematics, assessing the active stress field, and characterizing the physical properties of the rocks in the seismogenic zone. The identification and characterization of active faults in high-hazard areas such as Calabria are crucial for improving seismic hazard assessments and, ultimately, reducing seismic risk.

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From paper to pixel: reviving legacy seismic data through digitization, preconditioning, and attribute analysis in the tectonically active offshore sector of Pesaro–Fano, Adriatic Sea, Italy

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Keywords: legacy seismic data, seismic attribute analysis, Adriatic sea italy.

In recent years, seismic data processing software has advanced considerably, enabling more effective data enhancement and analysis of 2D and 3D datasets using techniques like data preconditioning, attribute analysis among others. These tools are broadly used in high-resolution surveys in geoenergy projects, including traditional applications like hydrocarbon exploration, as well as for emerging environemtaly friendly use such as carbon capture and storage (CCS). However, the application of these tools is not limited to modern digitally available datasets. They can also be highly effective on reprocessing of legacy seismic data. This is increasingly important as many countries are now releasing large volumes of historical seismic records, often available only as scanned images of hard-copy sections, through public declassification programs. Despite limitations related to age, scanning quality, and original acquisition methods, legacy seismic data can still offer valuable geological insights, especially in tectonically active regions. When reprocessed with modern digital workflows, these datasets can significantly improve our understanding of subsurface structures, representing an important application in seismotectonic studies and improving seismic hazard assessments. The present study focuses on the offshore area between Pesaro and Fano (Northern Adriatic Sea, Italy), where legacy seismic profiles acquired in the 1960s were digitized using the WIGGLE2SEGY Matlab tool and converted to SEG-Y format. The data were subsequently processed with a customized processing workflows including random noise suppression, spectral balancing, and amplitude normalization, to improve the signal quality and enhancing the visibility of low-amplitude reflectors and fine-scale structural features. Following this preconditioning strategy, a set of seismic attributes analysis was computed to highlight stratigraphic and structural discontinuities and particularly to refine the interpretation of the major thrust faults, which in the regional framework, have potential to be seismogenically active. Our results demonstrate that, with careful digitization and processing, legacy seismic profiles can yield valuable information on fault kinematics and subsurface structures. This underscores the importance of re-using historical geophysical data to support seismic hazard assessments, structural geology studies, and sustainable subsurface management. Unlocking the potential of archived datasets can reduce or optimize new costly acquisitions and helps ensure that valuable data remains accessible for future geoscientific research.

Historical Seismograms and Moment Tensor Analysis: Insights from Three Earthquakes in Southern Italy

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Keywords: historical seismograms, moment tensor inversion, Southern Italy.

The study of historical earthquakes has proven increasingly crucial for refining seismic hazard evaluation and risk analysis. This work introduces a comprehensive methodological framework for the recovery and interpretation of analog seismograms, aimed at improving our knowledge of past seismic events and their relevance to both local and regional seismotectonic models. We focus on three significant earthquakes that occurred in southern Italy: the 1947 Squillace Basin event (Scolaro et al., 2024), the 1968 Belice sequence (Orecchio et al., 2021), and the 1978 Ferruzzano earthquake (Orecchio et al., 2019). These events, located within the geodynamically complex and high-seismic-risk Southern Italy region, highlight the potential of analog seismogram analysis for historical earthquake characterization. For each event, we adopted a structured workflow involving the selection, digitization, and processing of historical records. Instrument response corrections were carefully applied, and the quality of the data was critically evaluated to ensure reliable results. A tailored time-domain waveform inversion technique, optimized for pre-digital datasets, was employed to derive moment tensor solutions (Stich et al., 2005). This enabled us to extract key seismic parameters such as fault geometry, hypocentral depth, and moment magnitude, offering new perspectives on the region's tectonic setting.

Specifically, the 1947 Squillace Basin earthquake was characterized as a Mw 5.1 event featuring left-lateral motion along a WNW–ESE striking fault, consistent with the STEP fault activity at the northern boundary of the Calabrian subduction zone. The 1968 Belice sequence predominantly involved reverse faulting along east- to northeast-striking structures, clarifying long-debated uncertainties regarding its source mechanism. The 1978 Ferruzzano earthquake, which previously had conflicting interpretations, was re-evaluated as a Mw 4.7 event involving normal faulting along a N-S oriented fault.

Our results emphasize the crucial value of analog seismograms in extending the instrumental record, enhancing the definition of seismic source parameters, and improving tectonic interpretations. Moreover, the successful application of modern inversion methods to historical data sets a precedent for future studies focusing on early instrumental seismicity. By addressing the challenges related to data preservation, digitization, and processing, this study contributes to wider efforts aimed at developing thorough historical earthquake catalogs, which are essential for improving seismic hazard models and supporting informed risk mitigation strategies.

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First estimate of the long-term fault displacement and slip rates of the Anghiari normal fault (Northern Apennines, Italy)

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Keywords: active normal faults, tectonic geomorphology, cosmogenic nuclides dating.

The Anghiari ridge, located in the Sansepolcro basin of the Upper Tiber Valley (Northern Apennines, Italy), is an asymmetric relief made of Pleistocene continental deposits and bounded to the east by the NE-dipping Anghiari normal fault (Benvenuti et al., 2016). At its summit lies a well-preserved paleosurface likely dating to the Mindel-Riss interglacial period (Cattuto et al., 1995), while smaller discontinuous paleosurfaces appear on the ridge's eastern flank. These surfaces are separated by various segments of the Anghiari fault, but until now, no chronological constraints were available. To address this, high-resolution geomorphological analysis and surface exposure dating using cosmogenic nuclides (e.g., ^{36}Cl and ^{10}Be) were applied to determine the ages of displaced landforms and quantify fault slip rates, crucial for assessing fault activity across different timescales. Using Pleiades satellite imagery and LiDAR-derived digital terrain models, we mapped paleosurfaces, fault scarps, and associated geomorphological features. Projecting the risers of the paleosurfaces along the drainage direction allowed measurement of vertical displacements and gully incisions. To date surface exposure, limestone and sandstone pebbles were sampled from two depth profiles at different fault positions and analyzed for ^{36}Cl and ^{10}Be concentrations using isotope dilution accelerator mass spectrometry (Schimmelpfennig et al., 2011). The measured exposure ages revealed consistent results of 42±9 kyr at the hanging wall and 40±9 kyr at the footwall of the Anghiari fault. The mapped paleosurfaces on the ridge's eastern slope dip 1-6° NE and appear morphologically consistent with terraces incised by SW–NE-oriented gullies, suggesting, together with the age consistency, they originated as a single erosional surface related to early ridge uplift and were later offset by faulting. Vertical displacement along the Anghiari fault ranges from 23 to 43 m (29-54 m along dip). Based on the computed exposure ages, the resultant slip rate for the Micciano fault is 0.6-1.3 mm/yr which is notably higher than the 0.1–0.3 mm/yr slip rate derived from paleoseismological data for the last 25 kyr (Testa et al., 2023). This discrepancy may reflect either overestimation due to dating uncertainties or actual variations in fault activity over time, potentially due to alternance of earthquake clustering and longer recurrence time or a slow-down of the fault activity over the last 25 kyr, or both. In conclusion, quantitative geomorphology and cosmogenic nuclide dating together provide critical insights into fault evolution, enabling the reconstruction of fault displacement, and long-term slip rates, thereby enhancing understanding of the Anghiari fault's seismic history.

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S11.

Mountain belts: natural laboratories for the short- and long-term rheology of the lithosphere

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CO_2-rich fluids and fault mechanics: Experimental and rate-and-state modelling of carbonated serpentinite friction in a subduction channel

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Keywords: fault mechanics, slip behaviour, fluid-rock interaction.

The frictional behaviour of shear zones is strongly influenced by their mineralogical composition, which can be further modified by fluid–rock interaction. In particular, carbonation of serpentinites – a process that produces rocks enriched in carbonates, quartz and phyllosilicates – can introduce substantial mechanical heterogeneity along subduction shear zones.

To investigate the effects of carbonation on fault mechanics, we conducted double direct shear biaxial deformation experiments on gouges derived from serpentinites with varying degrees of carbonation, sampled from a fossil subduction plate boundary exposed on Elba Island (Italy). We analysed seven samples representative of the carbonation gradient: from antigorite-rich serpentinite, through ophicarbonate, to a fully carbonated talc–carbonate–quartz mélange. Gouges (< 125 μm) were deformed in the BRAVA apparatus under 100 MPa normal stress, with a range of slip velocity from 0.3 to 1000 μm s^{-1}, at room temperature and under water-saturated conditions.

Frictional properties vary systematically with mineralogical composition. The antigorite-bearing serpentinite exhibits the highest friction coefficient (μ = 0.30–0.35) if compared to ophicarbonate and fully carbonated assemblages which show lower friction (μ = 0.24 and 0.12, respectively). In addition, we observed that antigorite-bearing serpentinites show velocity-weakening behaviour, whereas ophicarbonate and fully carbonated assemblages show velocity-strengthening behaviour.

Our results provide new constraints on the role of fluid-mediated mineral transformations in controlling the slip behaviour of subduction interfaces, with implications for the seismic potential of heterogeneous shear zones.

Strain localization at eclogite-facies conditions: interplay between fluids, metamorphism and deformation (Mt. Emilius klippe, Western Alps)

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Keywords: fluid-rock interaction, strain localization, eclogite.

Ductile deformation in massive rocks is often localized to discrete zones of high shear strain that commonly nucleate on precursor brittle fractures. Fractures promote redistribution of fluids in the host rock, that influence rock rheology by fostering the kinetics of metamorphic reactions. Reaction-induced grain-size reduction has long been considered one of the most effective strain weakening mechanisms. However, hydration may also cause rock hardening, and hydrated, fine-grained aggregates formed by metamorphic reactions have been observed to survive deformation. Here, we investigate the effects on rock rheology of eclogite-facies hydration of mafic granulites and ultramafites from the Austroalpine Mt. Emilius Klippe (W. Alps). In the ultramafites (diopside (Di), enstatite, plagioclase (Plg) websterites (Benciolini, 1996), the complete replacement of locally continuous Plg layers by eclogitic, fine-grained (down to 2 μm) aggregates of jadeite, quartz, kyanite and clinozoisite (Czo) did not result in strain localization, indicating that grainsize reduction alone is not always efficient in localizing strain.

In the mafic granulite, the original garnet (Grt), Di, Plg and hornblende assemblage was replaced by Grt, omphacite (Omph), amphibole, phengite, chlorite and Czo during Alpine eclogite-facies metamorphism (Pennacchioni, 1996). Early Alpine deformation developed a pervasive eclogitic foliation promoted by complete transformation of Plg to Czo (few tens of μm in size) aggregates. A second eclogitic deformation event consisted of localized ductile deformation closely linked to development of Czo and Grt-filled veins and associated Omph-rich alteration haloes. Ductile shear is often localized to the outer boundary of haloes forming paired shear zones, suggesting that extensive replacement of the Czo aggregates by Omph induced hardening of the reacted rock volume. Formation of a hardened metasomatic halo, however, did not always result in shear zone development at its outer boundary.

A set of samples ranging from haloes with flanking shear zones to haloes lacking shear localization was collected to investigate the role of fluid-rock interactions on shear zone nucleation. In strain-free samples, Omph accommodates deformation homogenously across the halo, dominantly by diffusion creep (weak CPO, random distribution of misorientation angles, rare subgrains).

EDS and *in-situ* LA-ICP-MS analysis suggests that propagation of the reaction front in the host rock forms a compositional gradient across the halo, mainly recorded by Czo reaction rims. Czo rims show a progressive enrichment in REE and Fe^{3+} towards the reaction front, usually related to an increased H_2O content (Schorn et al., 2023). We propose that the fluid diffused in the host rock until reactants were available and that the reaction occurred in the halo caused only minor H_2O consumption. As a result, H_2O accumulated at the reaction front promoting fluid-assisted deformation mechanisms.

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A journey into the Permian deep crust: a fieldtrip across the Valpelline and Arolla Series, Dent Blanche Tectonic System, Western Alps

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Keywords: migmatite, metaintrusive, Permian.

This fieldtrip aims to explore the Adriatic basement of the Valpelline and Arolla Series, which are part of the Dent Blanche Tectonic System in the axial zone of the Western Alps. This area represents a window into rocks and structures of the intermediate to deep continental crust, affected by partial melting, felsic and mafic intrusions during Permian, and successive Alpine deformation and metamorphism.

The fieldtrip is scheduled to take place over four days: i) in day 1 participants will be guided across the rock types of the deep continental crust, to examine different structures and discuss the relative and absolute geochronology of the deformation events during Permian partial melting in the Valpelline Series. In addition, the mylonitic contact between the Valpelline and Arolla Series will be reached; ii) day 2 is dedicated to smoothed outcrops of the Valpelline Series located at 2800 m a.s.l., showing melt-bearing textbook structures in cordierite-migmatitic gneiss, embedding mafic boudins. The structures are cut by multiple systems of aplites and pegmatites; iii) day 3 focuses on the Arolla Series metaintrusive bodies of the Permian Sassa gabbro Complex. The Sassa gabbro preserves different types of magmatic rocks, structures, and textures only locally overprinted by the polyphase Alpine deformation and metamorphism; iv) day 4 aims to explore the Arolla orthogneiss, the dominant rock type in the Arolla Series, within the Mont Morion intrusive complex along the Crête Sèche Valley above Dzovennoz. Although the orthogneiss displays varying degrees of Alpine deformation, developed under blueschist and greenschist facies conditions, it provides opportunities to study pristine magmatic textures, lithologies, and their relative chronology.

This geographical area located in the Western Alps represents a good archive to understand the geodynamic evolution of Adriatic crust during Permian time; the presence of several granitic plutons at shallow crustal levels, like those observed in the Arolla Series, suggests that melt extraction in the Valpelline Series could have been a continuous and efficient process during the Permian. In the Valpelline Series horizons extremely rich in sillimanite which crosscut the regional migmatitic foliation S2, serve as evidence for the interaction between the extracted melts and their host rocks.

Heterogeneous and cyclic brittle-ductile deformation as key structural signatures to understand deep slow slip and tremors in subduction zones

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Keywords: dilational shear veins, transient brittle-ductile deformation, subduction zones.

The geological record, spatial distribution and structural signatures of slow slip and tremors (SST) in subduction zones are still a matter of debate. Dilational shear veins, heterogeneously deformed rocks with a different rheology and brittle-ductile shear zones are considered to represent possible records of SST. The Liguro-Piemontese oceanic derived metasediments of the Western Alps in Italy, deformed at blueschist facies conditions (300-350 °C, 0.8-1.3 GPa, Agard et al., 2021), are a natural laboratory where investigate these processes.

We combined a multiscale characterization of a blueschist-facies exhumed shear zone with thermodynamic modelling and a quantitative study of deformation mechanisms to gain insights on deep SST. This hundred meter thick shear zone shows heterogeneously distributed strong marble lenses wrapped by weak graphitic schists, both deformed by sheath folds and veins. Hybrid veins in mylonitic marbles occur with crack-seal textures, oriented both parallel and at high angles to the main metamorphic foliation. The regional stretching mineral lineation is oriented NE-SW, both parallel to the carpholite fiber composing veins and to the sheath fold axes. A few carpholite veins are folded within mylonitic marble, attesting to cyclic switches between brittle and ductile deformation in the stability field of carpholite, i.e. under blueschist facies conditions.

We focus on deformed veins parallel to the foliation in which large quartz and Fe-Mg carpholite fibers (0.3210µm) deformed by incipient diffusion creep and grain boundary sliding. Some bands display a further grain size reduction and may suggest accelerated creep. Calcite paleopiezometry performed along these bands suggest differential stresses between 110-360 MPa and strain rates between 10^{-9} s^{-1} / 10^{-7} s^{-1}.

Multiple heterogeneously distributed brittle failure occurs preferentially in the stiffer marble bodies, as a function of the abundance and the interaction between the stiffer bodies and the weaker matrix. Hybrid veins resulting from a crack-and-seal cyclic process are reliable structural record of SST, and their sense of displacement is compatible with the seismic evidence for a double-coupled mechanism. Discrete slip and strain localization occurred by exploiting weaker horizons under transient and cyclic pore fluid pressure fluctuation, reaching sub-lithostatic values, and high strain rates, suggesting cyclic switching between seismic and aseismic conditions. These processes occurred at > 30 km depth in the lower transition zone of the Alpine subduction zone and are comparable with deep SST recorded in modern subduction zones.

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Shear zone-controlled migration of CO_2-bearing metamorphic fluids: Implications for mid-crustal seismicity and strain localization in orogenic belts

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Keywords: shear zone, metamorphic fluids, seismicity.

In orogenic settings, the release of deep metamorphic CO_2-bearing fluids is often associated with both deep and shallow seismic activity along major deformation zones. However, our understanding of the underlying mechanisms remains limited due to the scarcity of well-preserved fossil examples of such deformation zones that hosted CO_2-rich fluid flow. This gap also hinders the validation of models and interpretations based on geophysical and geochemical data. Current models suggest that deep-sourced metamorphic contribute to seismogenesis through fluid overpressure ("carbo-fracturing"), triggered by the separation of an immiscible CO_2-rich vapor phase from high-salinity brines at depth. At the same time, the high dihedral angles of CO_2-bearing metamorphic fluids restrict their mobility through quartzo-feldspathic crustal rocks. Consequently, the mechanisms enabling the transport of such fluids remain a fundamental open question.

We describe a set of shear zone-hosted, carbonate-bearing breccias from the crystalline units of the Gotthard Nappe, Aar, and Mont Blanc massifs (Central and Western Alps), which we interpret as evidence of regional-scale, fault zone-controlled flow of CO_2-rich metamorphic fluids during Alpine orogenesis. These breccias are confined to a pre-Alpine fault network that cuts through the crystalline basement. They are characterized by a matrix of coarse-grained (mm- to cm-scale) blocky calcite and dolomite enclosing angular clasts of the host rock. The abundant carbonate content, together with macro- and microstructural features, indicates formation via transient but recurrent (carbo-)hydraulic fracturing events involving CO_2-bearing fluids under amphibolite to greenschist facies conditions. Carbonate C–O–Sr isotopes and trace element geochemistry support a metamorphic origin of the fluids, isotopically equilibrated with the host basement.

We use field and microstructural observations to shed light on: (i) the possible preservation of microstructures indicative of immiscibility between carbonate- and quartz-bearing fluids; (ii) the interplay between tectonic deformation, fluid overpressure, stress drops potentially related to seismicity, and the resulting breccia micro- and meso-textures; (iii) the influence of carbonate breccia precipitation on ductile strain localization in mid-crustal shear zones, and its role in accommodating tectonic strain. Our integrated field, microstructural, and geochemical data suggest that these breccias represent fossil analogues of fault and shear zone networks that govern CO_2-bearing fluid flow in active orogenic systems. They provide valuable insights into crustal-scale carbonic fluid transport and its feedbacks on strain localization and tectonic deformation.

Shear zone growth by sequential generation of pseudotachylytes in the lower crust

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Keywords: pseudotachylyte, shear zone, brittle-ductile interplay.

Understanding the interplay between seismic and aseismic deformation in the lower crust is essential for constraining the rheological evolution of the crust over time. The Nusfjord locality in Lofoten, Norway, offers a unique natural laboratory for investigating these processes, as it exposes exhumed lower-crustal structures formed at depths of 25–35 km. The geological architecture consists of strong, low-strain granulitic anorthosite blocks bounded by ductile shear zones that host multiple generations of pseudotachylytes, formed by frictional melting during earthquake slip.

Field observations, photogrammetry, structural logs, and microstructural analysis reveal that pseudotachylytes systematically nucleate within the rigid blocks due to transient high-stress concentrations in the host rock (Campbell et al., 2020; Zertani et al., 2025). These transient seismic events occur during ongoing viscous creep within the shear zones, with ruptures once nucleated preferentially being attracted and following bimaterial interfaces (Brietzke & Ben-Zion, 2006) - such as shear zone/host rock boundaries or internal foliations - rather than cross-cutting them.

Quartz microstructures and EBSD-based quartz subgrain piezometry (Goddard et al., 2020) from quartz-bearing shear zones reveal heterogeneous stress distribution, suggesting fluctuating flow stresses associated with pseudotachylyte propagation. We observe synthetic or antithetic pseudotachylyte vein kinematics to the shear zone fabric reflecting the structural control exerted by the mylonitic host rock geometry and material contrasts. Shear zone width correlates with the spacing of adjacent zones: widely spaced zones enclose largely intact blocks with sparse pseudotachylytes, while closely spaced zones are thicker and bound more intensely fractured, pseudotachylyte-rich blocks.

We interpret that repeated cycles of pseudotachylyte generation, fracturing, and subsequent mylonitization promote the progressive incorporation of rigid blocks into the active ductile shear zones, resulting in the observed widening of the viscous shear zone and therefore mechanical weakening of the lower crust. Observed signatures of stress fluctuations further support the interpretation that seismic events induce transient stress pulses that influence viscous deformation.

Our findings highlight that pseudotachylytes are not merely the result of frictional-viscous switches within pre-existing shear zones but may reflect stress localization in strong domains adjacent to active ductile shear zones. Ultimately, repeated local switches between brittle and ductile deformation illustrate a feedback mechanism that governs not only the localization of deformation but the dynamically evolving rheological properties of the lower crust.

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Role of magnetite during deformation in serpentinite shear zones

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Keywords: magnetite, serpentinite, melange.

Magnetite is a common byproduct of the hydration of peridotite. Although magnetite is typically formed in relatively small modal quantities (< 10%), it can become concentrated along foliation and slip surfaces during deformation. In some cases, an interlinked network of magnetite-bearing surfaces can form. Given the rheological contrast between magnetite and serpentinite, this suggests that magnetite could play a significant role in controlling stress and strain localization within serpentinite shear zones.

We document the microstructure of polished magnetite slip surfaces (fault mirrors) from the Livingstone Fault in New Zealand. Magnetite is disseminated throughout the serpentinite shear zone matrix but also forms discrete and polished slip surfaces along the margins of pods embedded within the shear zone. The slip surfaces define the upper margin of a thin (typically 100–300 μm) and highly deformed magnetite slip zone containing inclusions of serpentinite. The presence of nanocrystalline olivine and enstatite within the inclusions has previously been related to a transient thermal spike induced by rapid slip along the slip surfaces.

EBSD and TEM analysis reveals a wide range of complex fabrics within the magnetite slip surfaces and slip zones. Magnetite precipitated in veins and slickenfibres dominates the uppermost part of the slip zone (immediately underlying the slip surface) and is characterised by aligned, elongate (> 100 μm long, 10 μm side) magnetite grains showing the local development of "brick-like" subgrain boundaries. Moving away from the slip surface, a sharp transition is observed to domains where the magnetite grain size is reduced by a factor of c. 10. These domains contain crenulated fabrics that evolve into closely spaced, chevron to isoclinal folds. The folds are cut by discrete, mm-scale thrusts and associated drag folds that displace multiple layers, as well as ultra-fine grained cataclastic shear zones up to 100 μm thick. TEM observations show that magnetite grains are surrounded by 50-500 nm thick rims of amorphous to partially crystalline serpentine.

Our observations suggest that the slip surfaces and slip zones preserve evidence for cyclic alternations of creep and brittle deformation, and that local enrichment of magnetite along foliation and slip surfaces can constitute an important mechanical and rheological heterogeneity in serpentinite-bearing shear zones.

Insights into the role of exhuming shear zones in subducted continental units (Oman Mountains)

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Keywords: fluid-rock interactions, shear zones, deformation mechanisms.

Exhuming shear zones are key structures in the dynamic evolution of orogens. Such shear zones accommodate most of the shear-related exhumation within relatively small rock-volumes. This is possible due to major strain partitioning occurring along weak rocks, frequently represented by phyllosilicate-rich rocks. Thus, the study of phyllosilicate-rich mylonites can provide fundamental insights into exhumation mechanisms responsible for the architecture of orogens.

The Hulw Shear Zone in the Saih Hatat Window of Oman (Agard et al., 2010) is one of these exhuming shear zones juxtaposing two subducted continental tectonic units. This tectonic contact experienced sustained shearing, accommodating a delta pressure of circa 0.8 GPa between 1.2 and 0.4 GPa at a relatively constant temperature of circa 400 °C (Petroccia et al., 2025) between 77 and 74 Ma (Ring et al., 2024).

In the field, micaschist belonging to the footwall displays a strain gradient moving toward the contact with the hanging wall, corresponding to the development of a S-C-C' fabric and a modal enrichment in K-rich white mica and pyrophyllite matched by a progressive increase in the physical alignment and interconnectivity of these phyllosilicates. Electron backscatter diffraction analyses suggest that large (hundreds of µm) quartz grains experienced grain size reduction by subgrain rotation recrystallization to form equant grains of less than 70 µm in size. Interconnected chains of small quartz grains are located in contact with the phyllosilicates, suggesting more efficient grain recrystallization.

Hyperspectral cathodoluminescence highlights different luminescence for the larger grains, producing a bright signal related to yielded cracks and fluid inclusions, and smaller equant grains, darker in cathodoluminescence and devoid of cracks.

In pyrophyllite-muscovite intergrowths, Transmission Electron Microscope analyses highlight generally more defects and kinking in pyrophyllite than in muscovite, intergrowths of crystallites down to 20 nm and truncated grain boundaries, likely reflecting dissolution and precipitation mechanisms.

Summarising, these results suggest that strain localization and weakening of this rock volume was achieved by an interplay of the following mechanisms: I) synkinematic nucleation of retrograde mineral phases along discrete C and C' planes, forming an interconnected network of phyllosilicates, II) diffuse microcracking associated with fluid flow in larger quartz grains, followed by subgrain rotation recrystallization leading to a finer grain size of quartz, III) more efficient recrystallization of quartz grains in proximity of phyllosilicates and IV) dissolution and precipitation processes. Concluding, this intimate and polyphase interplay between deformation and metamorphism is responsible for the formation and evolution of exhuming shear zones and the related structure of orogens.

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Agard P. et al. (2010) - Crustal stacking and expulsion tectonics during continental subduction: P-T deformation constraints from Oman. Tectonics, 29(5), https://doi.org/10.1029/2010TC002669.

Petroccia A. et al. (2025) - Sustained strain localisation and coeval brittle-ductile deformation in an exhuming low-grade shear zone: Insights from the Saih Hatat Window (NE Oman). Journal of Structural Geology, 191, https://doi.org/10.1016/j.jsg.2024.105328.

Ring U. et al. (2024) - The Samail subduction zone dilemma: Geochronology of high-pressure rocks from the Saih Hatat window, Oman, reveals juxtaposition of two subduction zones with contrasting thermal histories. Earth-Science Reviews, 250, 104711, https://doi.org/https://doi.org/10.1016/j.earscirev.2024.104711.

Polycyclic creep-to-brittle transition in serpentinite-rich fault zones: a multidisciplinary approach (Voltri Massif, NW Italy)

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Keywords: Voltri metaophiolite, polyhedral serpentine, RETURN.

The investigation of seismic source processes and wave propagation in heterogeneous rock media is one of the keys to improve seismic risk assessments, especially in low-seismicity, densely populated areas where the direct investigation of historical paleo-earthquake is difficult or even impossible.

The hinterland of the city of Genova (NW Italy), located at the eastern edge of the Alpine Voltri metaophiolite massif, is a natural laboratory to investigate (i) the interaction between rock faulting and fluid circulation during (potential) paleo-seismic cycles and (ii) the detection, location, and source characterization of possible earthquakes along tectonic lineaments developed inland and offshore the city, in the Ligurian Sea.

In the framework of the PNRR research program RETURN (Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate), we carried out a multi-scale and multidisciplinary approach focused on (i) the structural and petrographic characterization of serpentinite fault rocks, (ii) the detailed characterization of serpentine polymorphs crystallized along shear bands in the faults planes and their impact on the faults strength and (iii) the analysis of the microseismic events with Magnitude <= 2, potentially linked to active tectonics.

The structural and petrographic characterization of selected fault zones has revealed a complex, multi-stage deformation history, with older ductile structures (paragenesis: antigorite + ilmenite ± chlorite ± pyrite ± chalcopyrite, ascribed to the alpine-subduction and collision stages) cut by steeply dipping, NNE-SSW striking fault planes. These latter display multiple, anastomosed fault cores consisting of serpentinite-rich ultracataclasites (made of antigorite clasts embedded in chrysotile + chlorite rich matrix) bound by shear bands hosting polyhedral serpentine.

The fault cores textures (e.g., foliated and massive cataclasite), the paragenesis of newly formed shear bands and fault rocks matrices (polyhedral serpentine, chrysotile and chlorite) and the occurrence of mm-thick, cryptocrystalline oxide-rich fault mirrors suggest the occurrence of polycyclic creep-to-brittle transition in the same serpentinite-rich fault patch.

Finally, the NNE-SSW orientation of these faults subparallel to the Plio-Pleistocene lineaments identified in the Gulf of Genova and the associated NNE-SSW-oriented seismic epicenters cluster (characterized by few but continuous micro-earthquakes detected thanks to the installation of a temporary seismic deployment; https://distav.unige.it/rsni/return.php?lang=it) suggest recent regional scale tectonic activity also in the vicinity of Genova hinterland.

The critical role of amphibole in strain localization of HT mylonites (Ivrea-Verbano Zone, Southern Alps, Italy)

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Keywords: shear zone, deformation mechanisms, rheological modelling.

Mylonites preserved in exhumed lower crust sections provide an accessible window into deep processes governing the initiation of crustal shear zones at HT conditions. We performed microstructural and geochemical investigations on the Anzola shear zone, which is a major extensional structure from one of the best-preserved cross-sections through the middle to lower continental crust of a fossil passive margin, the Ivrea-Verbano Zone (Southern Alps, Italy; Corvò et al., 2022, 2023). Shear zone consists of banded mylonites of amphibole-rich and clinopyroxene/plagioclase-rich layers developed at HT amphibolite-facies (850-650°C, 0.7 GPa), locally encompassing thin amphibole-plagioclase ultramylonites. The Amph-rich layers display a core and mantle fabric with large porphyroclasts of pargasites and diopside embedded in a matrix composed of ubiquitous fine-grained plagioclase interdigitated with tails dominated by recrystallized hornblende. The Cpx/Pl-rich domains exhibit a few elongated or sigmoidal porphyroclasts of diopside embedded in a matrix of fine-grained plagioclase interdigitated with low pronounced tails of mixed recrystalized diopside/hornblende and plagioclase. Pervasive fracturing occurs in both amphibole and pyroxene. Grain size in the banded mylonite displays a strongly bimodal distribution, with the matrix characterized by an extreme grain size reduction enveloping large amphibole and/or clinopyroxene porphyroclasts. EBSD-based investigations on SPO and CPO suggest that deformation developed through the combination of coexisting deformation mechanisms (including precipitation/recrystallization processes, crystal plastic deformation and grain boundary sliding) active in the different microstructural areas of the mylonites. The thin ultramylonitic layer is instead dominated by highly mixed, fine grained neoblasts of amphibole and plagioclase, free of internal strain, suggesting the activation of grain boundary sliding processes. Rheological modelling through MyFlow (Casini et al., 2023) of the grain-scale distribution of effective deformation mechanism, stress, and strain-rate allows to evaluate the processes that yield to strong partitioning of stress and strain rate in the shear zones. New data are discussed highlighting the role of the amphibole in promoting strain localization.

Casini L. et al. (2023) - MYflow-A simple computer program for rheological modelling of mylonites. Journal of Structural Geology, 177, 105006, https://doi.org/10.1016/j.jsg.2023.105006.

Corvò S. et al. (2022) - Role of inherited compositional and structural heterogeneity in shear zone development at mid-low levels of the continental crust (the Anzola shear zone; Ivrea-Verbano Zone, Southern Alps). Lithos, 422, 106745, https://doi.org/10.1016/j.lithos.2022.106745.

Corvò S. et al. (2023) - Crystal plasticity and fluid availability govern the ability of titanite to record the age of deformation. Earth and Planetary Science Letters, 620, 118349, https://doi.org/10.1016/j.epsl.2023.118349.

Geologic evidence of earthquakes along a Miocene detachment (Waterman Hills Detachment, California)

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Keywords: earthquake, rock pulverization, detachment.

The mechanics of slip on low-angle extensional faults is unfavorable in Andersonian mechanics, creating a long-standing conundrum in tectonics. However, shallowly-dipping (≤ 35°) extensional faults can sometimes generate large-magnitude (Mw > 6) earthquakes rupturing to the surface. We describe the polyphase deformation history of the footwall block of the Miocene Waterman Hills Detachment (Mojave Metamorphic Core Complex, California). The Waterman Hills Detachment accommodated ~40-50 km of displacement and juxtaposes syn-extensional Miocene volcanic and sedimentary sequences onto amphibolite-facies metasedimentary and mafic rocks, and syn-extensional granitoids. Early doming of the metamorphic core complex initiated at amphibolite-facies conditions and continued through greenschist-facies, resulting in NE- and SE-dipping mylonites with bivergent sense of shear, with concurrent intrusion and stretching of the granitoid pluton as documented by other authors (Fletcher et al., 1995; Walker et al., 1995). Greenschist-facies ductile shearing progressively localized into top-to-NE mylonitic and ultramylonitic horizons. The transition to brittle faulting at low angle is attested by gently-dipping (< 40°) chlorite-epidote-cemented foliated cataclasites. Meter-thick lenses of pulverized rocks are found in meta-chert and aplite dykes in the uppermost 10-20 m of the footwall, suggesting the propagation of seismic ruptures along the detachment. The final stages of brittle faulting both overprint and crosscut the detachment. Late brittle faulting records the interaction of hydrothermal fluids with both volcanic rocks and the crystalline footwall, through tourmaline-cemented cataclasites and fault mirrors, and steeply-dipping calcite/siderite-hematite-cemented faults cutting both the footwall and hanging wall blocks, pinning the current juxtaposition during final slip on the detachment. The finding of pulverized rocks isolated to the fine-grained crystalline quartz-rich lithologies suggests that rock pulverization occurred at low temperatures where these lithologies were stiffer than the other wall-rocks. Our observations are consistent with the transient stress anomalies caused by the propagation of earthquake ruptures into the shallow seismogenic zone, indicating that the detachment was seismically active.

Fletcher J.M. et al. (1995) - Large-magnitude continental extension: An example from the central Mojave metamorphic core complex. Geol. Soc. Am. Bull., 107, 1468-1483, https://doi.org/10.1130/0016-7606(1995)107<1468:LMCEAE>2.3.CO;2.

Walker J.D. et al. (1995) - Connection between igneous activity and extension in the central Mojave metamorphic core complex, California. J. Geophys. Res. Solid Earth, 100, 10477-10494, https://doi.org/10.1029/94JB03132.

Geological record of deep-crustal earthquakes caused by bending of the lower plate during continental collision (Lofoten, Norway)

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Keywords: earthquakes, lower crust, continental collision.

The origin of earthquakes in the lower continental crust, where dominantly viscous deformation is expected, is highly debated. Available examples of field-based studies establish that (1) lower-crustal seismicity is generally linked to brittle failure of dry, strong rocks under fluid-absent conditions, and (2) lower-crustal earthquake sources typically consist of networks of coeval pseudotachylytes (quenched frictional melt produced during seismic slip) and mylonites (produced during post- and interseismic viscous creep). Despite these findings, it is often difficult to link the geological record of lower-crustal seismicity to specific tectonic settings.

The Nusfjord East shear zone network (Lofoten, Norway) is an exhumed lower-crustal earthquake source, where mutually overprinting mylonites and pseudotachylytes record the interplay between coseismic slip and viscous creep at depths of 25–30 km (Menegon et al., 2017). The network consists of two main intersecting sets of viscous shear zones, which commonly rework former pseudotachylyte veins. Mutual crosscutting relationships indicate that the two sets were active at the same time. The shear zones separate relatively undeformed blocks of anorthosite that contain pristine, small-scale (up to 15 m long with centimetres of slip) pseudotachylyte fault veins recording low-magnitude seismicity and normal-oblique kinematics. These pseudotachylytes are the fossilized seismogenic faults resulting from earthquake nucleation triggered by local stress amplifications in rigid blocks bounded by active viscous shear zones (Campbell et al., 2020).

Although best preserved in Nusfjord, structures with the same orientation and kinematics have been observed in different localities across a 25 km long transect through the Lofoten islands, indicating a regional significance. The coeval activity of the two main shear zone sets in Nusfjord is consistent with a local setting conducive to normal faulting, with a bulk vertical shortening and a horizontal NNW-SSE extension. This extension direction is subparallel to the convergence direction between Baltica and Laurentia during the Caledonian Orogeny. Pristine and mylonitized pseudotachylytes both formed at 426 ± 19 Ma (Zertani et al., 2024), which indicates an origin during the collisional stage of the Caledonian Orogeny. Present-day Lofoten is part of the Baltica plate; the lower plate during the Caledonian continental collision.

(Micro)seismicity in the lower crust in collisional orogens is commonly localized in the lower plate and has predominantly extensional and strike-slip focal mechanisms. This has been tentatively correlated with slab rollback and bending of the lower plate (Copley et al., 2011). We propose that the exhumed earthquake source in Lofoten represents the rheological response of the lower crust to bending of the lower plate during continental collision, thus providing direct observational constraints on a fundamental orogenic process.

Campbell L.R. et al. (2020) - Earthquake nucleation in the lower crust by local stress amplification. Nature Communications, 11, 1322, https://doi.org/10.1038/s41467-020-15150-x.

Copley A. et al. (2011) - The 2001 Mw 7.6 Bhuj earthquake, low fault friction, and the crustal support of plate driving forces in India. Journal Of Geophysical Research, 116, B08405, https://doi.org/10.1029/2010JB008137.

Menegon L. et al. (2017) - Earthquakes as precursors of ductile shear zones in the dry and strong lower crust. Geochemistry, Geophysics, Geosystems, 18, https://doi.org/10.1002/2017GC007189.

Zertani S. et al. (2024) - Dating fossil lower-crustal earthquakes by in-situ apatite U-Pb geochronology. Earth and Planetary Science Letters, 630, 118621, https://doi.org/10.1016/j.epsl.2024.118621.

From High-Pressure metamorphism to orogen-parallel exhumation driven by extensional shearing: the case of the Adula unit, eastern Central Alps (S Switzerland)

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Keywords: Adula unit, $^{40}Ar/^{39}Ar$ dating, San Bernardino eclogites.

The Adula nappe in the Central Alps is composed predominantly of metamorphic rocks, including orthogneiss of pre-Permian magmatic age and paragneiss. Ultramafic and mafic (U)HP lenses are preserved in the structurally upper parts of the unit and within the Cima Lunga subunit.

Tectonically, the Adula nappe is sandwiched between non-eclogitic Sub-Penninic nappes below, derived from the distal European margin, and non-eclogitic Middle Penninic nappes (Tambo and Suretta) above, which originated from the pre-Permian basement and Mesozoic cover of the Briançonnais domain. The contact between the Adula and Tambo nappes is marked by a complex shear zone (Pescion and Misox zones), composed of tectonic slices of Adula-derived gneisses, dolomitic marbles, cargneule, micaschists, calcschists, and greenschists. NNW-directed nappe stacking of the Adula, Tambo, and Suretta units involved pervasive mylonitic shearing, reflected in penetrative NNW-trending stretching lineations within all three units.

To account for the existing structural framework and the metamorphic discontinuity between the (U)HP Adula nappe and the overlying eclogite-free nappes, a normal-sense shear zone must have been active during exhumation. This shear zone likely accommodated the pressure gap and facilitated the upward movement of the Adula nappe during the tectonic evolution of the Central Alps.

We documented this shear zone in the San Bernardino Pass region (Switzerland), identifying it between the top of the Adula nappe and the base of the Misox zone. The zone is primarily developed within Adula orthogneisses and eclogite-hosting paragneiss layers at its upper boundary.

In these rocks, an early NNW-directed stretching lineation (quartz + white mica + biotite) is overprinted by a secondary NE- to SE-trending lineation, defined by quartz + white mica, and associated with top-to-E extensional shearing. Structural relationships show that the mylonitic lineation (omphacite ± quartz) in eclogitic boudins is consistently rotated with respect to the host fabric, indicating that these high-pressure blocks rotated during deformation, and that their internal foliation predates the extensional shearing phase. Peak metamorphic conditions in the eclogites, characterized by omphacite + garnet + phengite + clinozoisite + kyanite + Na-amphibole, are constrained at ~2.0-2.1 GPa and 520-645 °C. $^{40}Ar/^{39}Ar$ dating of syn-kinematic phengite along the foliation yields ages between 37 and 39 Ma. In the mylonitic orthogneiss, $^{40}Ar/^{39}Ar$ data exhibit an eastward younging trend from ~37 Ma at the base to ~29 Ma in the eclogite-bearing upper levels. This trend supports a scenario of top-to-E extensional shearing that began soon after HP peak metamorphism recorded in the eclogite lenses.

The fairytale story about the origin of elongated honeycomb garnets in a major high-pressure continental shear zone, Oman

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Keywords: strain, deformation, metamorphic reactions.

Garnet is one of the most useful minerals for studying a wide range of geological processes due to its sensitivity to geological changes and its resistance to strain. Although garnet usually forms isotropic crystals, garnets can grow differently, producing peculiar shapes, as elongated or honeycomb garnets. However, elongated and honeycomb garnets occur commonly if melt is present and are rare at high-pressure conditions (e.g., Hawkins et al., 2007). Moreover, no univocal processes have been invoked to explain their growth.

To address this scientific question, we studied a garnet-bearing quartz schist from the As Sheik Shear Zone (ASSZ) in the Saih Hatat Window of NE Oman. This major shear zone played a key role in the exhumation history of the continental eclogite-facies rocks. Both elongated and isotropic garnets are present in the sample. Elongated garnets locally show a prismatic shape, overgrown by a honeycomb structure within the quartz grain boundaries. Electron backscatter diffraction highlights that garnets are single grains without internal deformation, demonstrating that elongated garnets do not precede shear deformation and suggesting that garnets may form syn-kinematically or during the late activity of the shear event.

The initial elongated and prismatic shape of garnet can be explained by pseudomorphosis on reported peak pressure phases in the ASSZ (e.g., chloritoid, phengite or epidote; Warren & Waters, 2006). Indeed, the breakdown reactions of the previous mineral phases with quartz consumption can induce garnet growth with a considerable amount of free H_2O liberated in the system. The destabilisation of quartz can produce transient porosity that can enhance garnet growth at former grain boundaries, thus explaining the honeycomb structure.

Due to the relatively low modal amount of phyllosilicates, we can speculate about fluid migration, causing both pore fluid pressure fluctuations and enhancing the growth of hydrous phases and, possibly, the retrocession in other sectors of the shear zone. This interpretation is supported by the presence of dilational hydroshear veins formed by hydrous phases (i.e. blue amphibole) and compartmentalised retrograde metamorphism within phyllosilicate-rich bands.

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Hawkins A. et al. (2007) - Origin and mechanical significance of honeycomb garnet in high-pressure metasedimentary rocks from the Tauern Window, Eastern Alps. Journal of Metamorphic Geology, 25(5), 565-583, https://doi.org/10.1111/j.1525-1314.2007.00714.x.

Warren C.J. & Waters D.J. (2006) - Oxidized eclogites and garnet-blueschists from Oman: P–T path modelling in the NCFMASHO system. Journal of Metamorphic Geology, 24(9), 783-802, https://doi.org/10.1111/j.1525-1314.2006.00668.x.

Interplay between strain localisation and dehydration metamorphic reactions in exhuming continental shear zones (Saih Hatat Window, Oman)

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Keywords: shear Zone, phyllosilicates, strain localisation.

Hydrous phases, as phyllosilicates, play a key role in controlling the rheology of shear zones, the style of deformation and the syndeformational fluid budget. The latter, including aqueous fluids released by metamorphic reactions, can transiently increase pore pressure and trigger cyclic switching between brittle and ductile deformation conditions. Unfortunately, it is still unclear how these processes act together in exhuming low-grade shear zones in a continental collisional framework.

To tackle this scientific question, we studied the Hulw Shear Zone in the Saih Hatat Window of Oman. This shear zone is responsible for part of the exhumation of the subducted continental crust, but its pressure-temperature (*P–T*) and deformation behaviour remain largely unconstrained. Its footwall is mostly composed of metapelites, with a modal enrichment in K-rich white mica and pyrophyllite, matched by a progressive increase in the physical interconnectivity of phyllosilicates along its internal strain gradient and confirmed with the aid of Micro-CT tomography. Similarly, marbles in the hanging wall evolve from mylonitic to ultramylonitic towards the core of the shear zone. The shear zone is characterised by two opposite deformation behaviours, with ductile deformation accommodated preferentially along laterally continuous phyllosilicate-rich bands and brittle deformation in the form of hybrid/dilational hydroshear veins found regularly at the outcrop.

Our thermodynamic calculations highlighted that the Hulw Shear Zone accommodated progressive shearing while exhuming its footwall from epidote blueschist to low-pressure greenschist facies conditions. Decompression-driven fluid-gain reactions facilitated the growth of synkinematic phyllosilicates, causing significant mechanical weakening as well as the potential for discrete and compartmentalised fluid cells within the mylonitic foliation. Brittle structures formed due to aqueous fluid released by metamorphic dehydration reactions close to peak-*P* conditions (e.g., kaolinite-out reaction) or along the exhumation trajectory, transiently increasing pore pressure and triggering brittle failure, resulting in coeval mylonitic foliation and crack-seal hybrid veins.

Our findings support that the Hulw Shear Zone might contain local records of deep episodic tremors and slow slip events during exhumation-related tectonics in the accretionary wedge above the subduction interface of the Oman continental lithosphere.

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Depth and Deformation: Investigating Block-in-Matrix Formation in Accretionary Prisms

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Keywords: accretionary prism, block-in-matrix, recumbent folds.

The block-in-matrix fabric observed in modern and ancient accretionary prisms throughout the world has been studied in recent years with respect to mixed brittle-ductile deformation processes, which in turn may be associated with slow earthquakes phenomena (e.g. Behr & Bürgmann, 2021). Many studies focus on slow earthquakes near the downdip limit of the seismogenic zone (~350°C) and implicitly assume that most of the deformation observed in outcrops predominantly developed at metamorphic depths or during subsequent exhumation. However, field observations indicate that the block-in-matrix fabric is not exclusively metamorphic in origin, but may form through sedimentary processes or tectonic processes (e.g. Festa et al., 2012; Remitti et al., 2024) already in the very frontal part of accretionary prisms and at diagenetic conditions. Starting from literature datasets, we present four examples from the exhumed accretionary prisms of the Northern Apennines and Western Alps. From the shallowest to the deepest, the case examples are: (i) the Ligurian Units in the Northern Apennines, Italy (Tmax < 100-150 °C), (ii) the Sestola-Vidiciatico and Subligurian tectonic units in the Northern Apennines, Italy (Tmax ~100–200 °C) , (iii) the Infrahelvetic Units in the Western Alps, Switzerland (Tmax ~170-320 °C) and (iv) the Schistes lustrés Complex in the Western Alps, along the Italian-French border (Tmax ~350-475 °C P > 1.2GPa). Our comparison of these examples suggests that block-in-matrix fabrics can record a prolonged deformation history and are not necessarily indicative of distinct pressure-temperature conditions. A pervasive mixed brittle-ductile block-in-matrix fabric can form at shallow structural levels due to sediment accretion and isoclinal folding before complete lithification. The eventual lithification of accreted sediments promotes strain localization and results in a brittle-frictional overprint on the block-in-matrix fabric. Upward migration of the plate interface and out-of-sequence thrusting can cause the deep burial of frontally accreted sediments, eventually leading to metamorphism. Temperature-dependent ductile deformation processes can further overprint inherited structures and amplify the block-in-matrix fabric. The shallow formation of the block-in-matrix fabric may be related to shallow slow earthquake phenomena in the upper plate accretionary wedge but also contributing to mechanical heterogeneities that later influence deeper earthquake behaviour.

Behr W.M. & Bürgmann R. (2021) - What's down there? The structures, materials and environment of deep-seated slow slip and tremor. Philos. Trans. A Math. Phys. Eng. Sci., 379(2193), 20200218, https://doi.org/10.1098/rsta.2020.0218.

Festa A. et al. (2012) - Mechanisms and processes of stratal disruption and mixing in the development of mélanges and broken formations: Redefining and classifying mélanges. Tectonophysics., 568-569, 7-24, https://doi.org/10.1016/j.tecto.2012.05.021.

Remitti F. et al. (2024) - Role of folding-related deformation in the seismicity of shallow accretionary prisms. Nat. Geosc., 17, 600-607, https://doi.org/10.1038/s41561-024-01474-6.

Coupled metasomatic and mechanical evolution of carbonated serpentinite at the subduction interface

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Keywords: serpentinite carbonation; strain localisation; seismic behaviour.

The rheological evolution of subduction interface shear zones is governed by the interplay between deformation and fluid-driven mineral transformations. In the Norsi-Cavo Complex (Island of Elba, Italy) (Papeschi et al., 2023), an exceptionally well-exposed fossil subduction channel preserves serpentinite-rich shear zones that underwent extensive carbonation and metasomatic alteration. Integrating field mapping, petrographic and 3D microstructural analysis, isotopic data, and thermodynamic modelling, we characterise how these processes changed rock composition and affected their mechanical behaviour at subduction depths of ~15-25 km.

Carbonation exploited shear zones within the serpentinite, generating carbonate, talc, and chlorite-bearing veins and breccias. In the Norsi area, these lithologies define shear zones where deformation is localised into foliated talc and tremolite schists, massive carbonate breccias, and block-in-matrix serpentinite mélanges. These zones preserve clear evidence for brittle fracturing, shearing, and reaction softening, coinciding with carbonation fronts and a transition in mineralogy from antigorite-dominated serpentinites to talc-rich assemblages. The development of these reaction zones appears to be both facilitated by and contributory to deformation: fluid ingress was permitted by shear bands and discontinuities, while the formation of mechanically weak minerals such as talc and chlorite reduced rock strength and accommodated further strain.

Our findings show that carbonation at the subduction interface is not merely a metasomatic overprint, but a dynamic process that transforms the mechanical architecture of the shear zone. The resulting rheological heterogeneity — marked by coexisting ductile, talc-rich domains, and brittle, carbonate breccias — has implications for strain localisation, subduction initiation, and the seismic behaviour of plate boundaries.

Papeschi S. et al. (2022) - Deformation and material transfer in a fossil subduction channel: evidence from the Island of Elba (Italy). Tectonics, 41(7), e2021TC007164.

Basement-cover relationships in the northern Dora-Maira Massif, Western Alps: the case of the Bussoleno Detachment Shear Zone

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Keywords: basement-cover interfaces, detachment shear zones, Dora-Maira Massif.

The northernmost sector of the Dora-Maira Massif (DMM) is a key area for studying the basement-cover relationships and the development of detachment zones, which commonly are important markers for understanding the multistage tectonic evolution of orogenic belts. In this area, differently from others sectors of DMM where the Mesozoic cover successions are tectonically sliced and completely detached from their Paleozoic basements (Balestro et al., 2022), primary basement-cover relationships seem to be preserved.

We investigated the DMM basement and cover successions in the Susa Valley (Western Alps), through the realization of a detailed geological map at 1:5,000 scale (Balestro et al., 2025) and by analysing two representative lithostratigraphic and structural sections across the former basement-cover interface. The Paleozoic basement consists of polycyclic garnet- and chloritoid-bearing micaschist with bodies of metabasite and of monocyclic augen gneiss, whereas the Mesozoic cover succession mainly consists of Triassic metadolostone with minor dolomitic marble and carbonate-bearing micaschist. Both the DMM successions were deformed during four main Alpine deformation phases corresponding to the subduction-related D1 phase and the early (i.e., D2) to late (i.e., D3 and D4) exhumation-related phases.

We found that the basement and cover successions are actually separated by a shear zone (the Bussoleno Detachment Shear Zone, BDSZ), varying in thickness from few meters to tens of meters and mixing blocks of different lithologies. Stratigraphic contacts has been extensively reworked along the BDSZ, which incorporates material sampled from the Paleozoic basement, the Mesozoic cover, and also lithologies not present in these successions such as carbonate tectonic breccia, carbonate- bearing quartzite, banded marble passing to mylonitic calcschist, and quartz-rich schist. These metasediments formed the original basement/cover interface and played a role in triggering the development of the BDSZ. The latter, as well as the Mesozoic and Paleozoic successions, have been deformed by both D2-, D3- and D4-related folds. This would indicate that the BDSZ enucleated during the subduction-related D1 phase, which exhibited N-NW vergence on a regional scale and developed under eclogite-facies P-T peak conditions.

Balestro G. et al. (2025) - Tectonic relationships between the Paleozoic basement and the Mesozoic cover succession in the northern Dora-Maira Massif (Susa Valley, Western Alps), Journal of Maps, 21(1), 2451785, https://doi.org/10.1080/17445647.2025.2451785.

Balestro G. et al. (2022) - Pre-Orogenic Tectonostratigraphic Evolution of the European Distal Margin-Alpine Tethys Transition Zone in High-Pressure Units of the Southwestern Alps. Geosciences 2022, 12, 358, https://doi.org/10.3390/geosciences12100358.

Importance of inherited rifted margin architecture on the structural evolution of continetal collision zones

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Keywords: numerical modelling, fold-and-thrust belts, rheology.

A large portion of localized deformation in continent-continent collision zones takes place along mechanically weak fault zones inherited from earlier tectonic processes, particularly those formed during multiple phases of continental margin rifting. In addition to these pre-existing weak zones, the thermal, rheological, and geometric properties inherited from earlier tectonic activity at continental margins can influence collision dynamics — either facilitating or hindering the subduction or accretion of fragments of continental lithosphere. Consequently, understanding the dynamics of earlier rifting events is essential for studying the structural and mechanical development of continental collision systems.

In this study, we explore how the rift-related architecture of continental margins influences collision by employing geodynamic numerical modeling. We use the two-dimensional finite-difference code Norma (Ruh, 2017), implemented on a locally refined, fully staggered Eulerian grid measuring 1000 x 200 km, alongside a Lagrangian marker field to track deformation. The numerical models simulate an initial phase of lithospheric extension, followed by tectonic quiescence, and then convergence, culminating in continental collision. Depending on the degree of extension and whether oceanic lithosphere formed, the early stages of convergence may involve oceanic subduction. During rifting, we explore variations in strength of the lower continental crust, resulting in narrow (strong lower crust) or hyper-extended continental margins (weak lower crust). Ultimately, we investigate the importance of syn-rifting sediment properties, the existence of serpentinite in the oceanic lithosphere, and syn-convergent surface processes on continental collision.

Results demonstrate that a weaker lower continental crust allows for the accretion of crustal terrains into the accretionary orogen, while large parts of stronger lower crust enters the mantle asthenosphere undeformed. Weak syn-fift sediments allow for the underthrusting of continental slivers that are ultimately accreted at larger depths, while strong syn-rift sediments lead to a wide subduction channel constituting continental crust and sediments in a mélange-type shear zone. This study sheds light on the specific pre-collisional conditions that shape natural orogens with rifted margins.

Ruh J.B. (2017) - Effect of fluid pressure distribution on the structural evolution of accretionary wedges. Terra Nova, 29(3), 202-210, https://doi.org/10.1111/ter.12263.

Supra- to subsolidus evolution of syn- to late-tectonic granitoids from Capo Vaticano Promontory (southern Calabria, Italy)

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Keywords: deformation microstructures, geological map, late Variscan.

This study presents new field and microstructural constraints into the batholith architecture and supra- to subsolidus evolution of late Variscan granitoids at Capo Vaticano Promontory, part of the ~13 km-thick Serre Batholith in southern Italy. A field survey, assisted by petrographic analyses, produced the first geological map of the area (1:140,000 scale), detailing magmatic unit relationships and their petro-structural features. A migmatitic border zone (MBZ) marks the transition from lower crustal paragneisses to the deepest emplaced granitoids. The oldest, deepest granitoids are strongly to moderately foliated amphibole-biotite tonalites and quartz diorites (ABT), transitioning to biotite tonalites and quartz-diorites (BT), which can be subdivided into strongly to moderately foliated (BTs) and weakly foliated to unfoliated (BTw). Clear intrusive contacts mark the passage from BTw to overlying weakly foliated-unfoliated porphyritic muscovite-biotite granodiorites and granites (PMBG). The study also revealed: a) a northern sector with a continuous batholith cross-section and b) a southern sector with an irregular distribution of the magmatic units due to post-Variscan tectonics. Microstructures document late-Variscan deformation starting at suprasolidus conditions (e.g., quartz chessboard patterns and submagmatic fractures in plagioclase) and evolving through progressively high- to low-temperature subsolidus stages (e.g., feldspar bulging, quartz recrystallization, mica kinking) for all the magmatic units. Continuous supra- to subsolidus deformation associated with a well-developed fabric suggests tectonic control on the emplacement and cooling of early tonalites/quartz diorites, while the emplacement of the porphyritic granitoids has occurred during waning tectonic activity stages in the framework of the post-collisional evolution of the south-western Variscan Belt.

Oceanic slab extraction from Ultra-High-Pressure conditions. The case study of the Lower Shear Zone, Monviso Massif, Western Alps

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Keywords: ultra-high pressure, subduction channel.

The dynamics of subduction zones and the mechanical behaviour of the plate interface at mantle depths play a key role in the short-term coupling of converging plates and the long-term orogenic cycle. Despite an increase in high-quality metamorphic, structural, and geochronological data and observations, the processes and mechanisms that drive the accretion of rock units from the subducting slab into the plate interface and their subsequent exhumation are debated. Many of these models suggest that in cold orogens the exhumation of (U)HP materials occur along the plate interface. Nevertheless, the geometries, the timing of initiation and propagation, the strain distribution and the mechanisms acting along these shear zones in the subduction channel are poorly documented. The exhumed high- and ultra-high-pressure (UHP) rocks stacked in fossil subduction-accretionary systems offer a window into these processes, and on the thermo-mechanical evolution of plate interfaces and the mechanisms operating in subduction channels. The Monviso Lower Shear Zone (LSZ; Lago Superiore Unit, Western Alps), is a ~25 kilometres -long UHP slice of former oceanic rocks accreted to the Alpine plate interface that preserves evolutionary snapshots of shear zone deformation within the plate interface (e.g., Angiboust et al., 2012; Ghignone et al., 2023; Scaramuzzo et al., 2025). The combination of structural and petrologic studies, from cartographic to microscopic scale, suggests that the LSZ was active during the different stages of subduction to exhumation in a subduction-accretion cycle (Scaramuzzo et al., 2025). Our multiscale approach enabled to correlate the mesoscopic mylonitic foliations with the microscale ones and those preserved in garnet cores. Our results show that detachment of this sliver from the subducting slab was favoured by the presence of fluid, which enhanced shear traction reduction. Moreover, the top-to-the hinterland (NE) sense of shear resulting from the analysis of kinematic indicators suggests that LSZ acted as a normal roof fault for the extraction of an extruding wedge during its progressive boudinage and disruption.

Angiboust S. et al. (2012) - Eclogite breccias in a subducted ophiolite: A record of intermediate-depth earthquakes? Geology 40, 707-710.

Ghignone S. et al. (2023) - A new UHP unit in the Western Alps: First occurrence of coesite from the Monviso Massif (Italy). American Mineralogist, 108(7), 1368-1375.

Scaramuzzo E. et al. (2025) - Subduction and extraction of an Ultra-High-Pressure oceanic subduction plate interface (Lower Shear Zone, Monviso Massif, Western Alps). ESS Open Archive.

Strain distribution and coseismic features along the subduction plate interface: the record of the Lower Shear Zone in the Monviso Massif (Italy)

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Keywords: plate interface, pseudotachylite, slow slip earthquake.

The geometry and thermomechanical processes of coseismic sources and fracture propagation along active subduction plate interfaces are inferred mainly from geophysical observations and numerical modelling. These observations shed light on the features and rupture processes acting at different depths along the plate interface, such as aseismic slip, episodic non-volcanic tremor and slip, and regular earthquakes. Nevertheless, despite the high amount of data obtained through indirect approaches, our understanding of the thermomechanical dynamics of coseismic ruptures along the plate interface at depth is still limited. Therefore, investigating the fossil record of rocks exhumed from high and ultra-high-pressure conditions (> 70 km) represents a natural probe to unveil the interplay of metamorphic reactions and fluids affecting plate interface rheology at depth with a grand scale resolution.

The Lower Shear Zone (LSZ) in the Monviso massif (W Alps) represents a fossil plate interface accreted within the Western Alpine chain and constitutes one of the few examples of an oceanic plate interface that has been exhumed after having reached the coesite stability field, i.e. ca. 90-100 km depth (Angiboust et al., 2012; Ghignone et al., 2023). Here, rocks involved in the LSZ show brittle to ductile behaviour experienced during their tectonometamorphic evolution. Brittle features correspond to the product of brecciation at eclogitic depth, i.e., eclogitic breccia, and greenschist recrystallised pseudotachylite veins.

These features are remarkably preserved in rigid gabbroic blocks embedded into a mylonitic serpentinitic-metasedimentary matrix. The eclogitic breccia consists of a matrix-supported, centimetre- to decimetre-thick, mosaic breccia. At the same time, the recrystallised pseudotachylites occur as millimetre-thick veins crosscutting the relict magmatic fabric of the dry metagabbro. Eclogitic breccia can be interpreted as the product of transient and cyclic low-velocity ruptures along the plate interface at ca. 70 km. At the same time, recrystallised pseudotachylites are related to regular velocity earthquakes. The difference in the thickness of the deformation zone agrees with a scaling law between the width of the shearing surface and the rupture speed (Kammer et al., 2024; Dal Zilio & Gerya, 2025). Our observation suggests that while regular earthquakes are likely to be systematically associated with extreme strain localisation, low velocity earthquakes could be related to centimetre- to decimetre-thick fracture propagation.

Angiboust S. et al. (2012) - Eclogite breccias in a subducted ophiolite: A record of intermediate-depth earthquakes? Geology, 40, 707-710.

Dal Zilio L. & Gerya T. (2025) - Poromechanical modeling of strain localization during earthquake rupture. EGU General Assembly 2025, Vienna, Austria, 27 Apr-2 May 2025, EGU25-14136.

Ghignone S. et al. (2023) - A new UHP unit in the Western Alps: First occurrence of coesite from the Monviso Massif (Italy). American Mineralogist, 108(7), 1368-1375.

Kammer D.S. (2024) - Earthquake energy dissipation in a fracture mechanics framework. Nature communications, 15(1), 4736.

S12.

Stressing the Apennines: from pre-orogenic to post-orogenic events

CONVENERS AND CHAIRPERSONS

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From Jurassic rifting to mountain building and collapse: The Mt Marine case (central Apennines)

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Keywords: structural inheritance, Apennine thrusting, active tectonics.

This study investigates the structural architecture of the Monte Marine area, along the northernmost shoulder of the L'Aquila Intermontane Basin (central Apennines). This region preserves key structural evidence of pre-, syn- and post-orogenic deformation. Through detailed structural field mapping and geological analysis, we constrain the structural architecture and evolutionary tectonic history of the area, emphasizing the complex interactions between inherited structures and deformation phases. Our results delineate three main tectonic stages since the Jurassic. A pre-orogenic extensional phase developed after the Tethys Ocean rifting (Early Jurassic), led to the formation of a dolomitized paleo-horst that significantly influenced subsequent deformation. Preliminary U-Pb carbonate dating on dolomite veins yields approximately 110-120 Ma, suggesting that tectonic activity might have multiple pulses from the Early Jurassic up to the Early Cretaceous. During the orogenic compressional phase, thrusts nucleated and propagated with geometries largely governed by the pre-existing structures. In proximity to the horst, NW–SE-trending high-angle ramps (~40–55°) and NE–SW lateral ramps developed, enveloping the inherited paleo-high. In contrast, thrusts farther east exhibit low-angle geometries (~29°) and are associated with left-lateral strike-slip faults. Low-T dolomite thermochronometry (TL) constrained the thrusting age to ca. 4.60 ± 0.35 Ma (Zhang et al., 2025). These compressional structures were later dissected by high-angle extensional faults formed during the Late Pliocene–Quaternary post-orogenic phase. High angle extensional faults frequently cut off the low-angle thrusts with fault zone localisation at the piedmont of the Monte Marine, likely reactivating favourably oriented pre-orogenic extensional faults. The onset of the post-orogenic tectonic activity is constrained between 2.4-2.7 Ma by TL dating of dolomite clasts and cataclasite from the footwall of the main normal fault plane (Zhang et al., 2025). U-Th ages on multiple syn-kinematic carbonate mineralizations along the main fault strands indicate multiple pulse of tectonic activity between 575 and 59 ka. This structural evolution highlights the critical role of inherited mechanical anisotropies in localizing regional deformation during both contractional and extensional phases. Overall, our findings enhance the understanding of spatial and temporal variability in deformation styles across the Apennine orogenic system.

Zhang J. et al. (2025) - Dolomite luminescence thermochronometry reconstructs the low-temperature exhumation history of carbonate rocks in the central Apennines, Italy. Commun Earth Environ., 6, 252, https://doi.org/10.1038/s43247-025-02216-1.

Subsurface structure and tectonic evolution of the Mugello Basin: insights from seismic microtremor measurements, geomorphic analyses and well log data

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Keywords: Mugello Basin, post-orogenic extension, Northern Apennines.

The main drainage divide of the Northern Apennines generally delineates the boundary between the internal part of the orogen, which is undergoing post-orogenic extension, and the frontal part of the belt, which is still experiencing contraction and nappe stacking. Extension in the most internal part of the belt (Tyrrhenian Sea) started in the Neogene and progressively migrated NE-ward leading to the formation of marine-to-continental to fully continental basins. However, debate exists on whether these basins formed only in response to post-orogenic crustal extension or if they were also influenced by crustal shortening during their evolution. The Mugello intermontane basin is a classic example of setting where such debate has grown, since it lies close to the main Northern Apennines watershed, a portion of the belt where the transition from compression to extension only occurred in relatively recent times.

The scarcity of outcrops and the lack of seismic cross sections resulted in significantly different interpretations regarding the structural architecture and the Quaternary tectonic evolution of the Mugello Basin. (i) Some authors propose a half-graben geometry with a main graben bounding fault along the southwestern margin, which formed under an extensional regime but also experienced pulses of compressional tectonics. (ii) Other authors claim for formation under a purely extensional tectonic regime, with an early stage as a synform shaped basin that later evolved in an asymmetric graben controlled by faults rooted at depth in a low-angle NE-dipping normal fault. (iii) A third model proposes the formation of the basin in a compressional tectonic setting and that extension only activated in recent times, controlling the present-day seismicity. Consequently, the active seismotectonic setting is largely debated and unconstrained.

To add key constraints on the architecture and evolution of the Mugello Basin, we integrated field observations, compilation of existing well data, morphometric analyses of the fluvial network and seismic microtremor measurements to be interpreted in the frame of the MHVSR method along one along-strike and four across-strike transects within the basin. The geophysical data allowed us to reconstruct the subsurface 3D geometry of the top basement in a synform geometry, with a main depocenter located in the central part of the basin. This reconstruction rules out the half graben hypothesis. The maximum thickness of the sedimentary fill is ca. 550 m. Moreover, we highlight a slight asymmetry of the top basement along the northeastern margin that suggests dislocations by normal faulting. Accordingly, morphometric analyses (Ksn and chi-values) highlight a disequilibrium in the river network along this margin. More in general, these results provide valuable insights into the Mugello Basin structural development within the broader shift from syn-orogenic compression to post-orogenic extension across the Northern Apennines.

Geological evolution of the Southern Apennine and role of pre-existing structures: examples from the Val D'Agri area

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Keywords: Val D'Agri field, faults reactivation.

The Val D'Agri field is the largest onshore oil field in Europe discovered in 1988. Since then, 3D seismic acquisition and different processing phases have been performed to better detail field geometry.

Several wells have been drilled in the area allowing both the improvement of the top reservoir in-depth placing and the definition of the structural framework.

The reservoir is given by the carbonatic Apulian Platform, Cretaceous to Upper Miocene in age. The main top seal is provided by the Middle-Upper Miocene shaly foredeep deposits belonging to the Irpine Unit. In some areas, its thickness exceeds 1km. Above it, the allochthonous complex (overburden), including highly deformed tectonic nappes involving the Triassic-Miocene Apenninic Platform, Lagonegrese unit, Sicilidi and Liguridi units, is present. This complex regional structural setting affects negatively the seismic imaging making seismic interpretation quite difficult and not always straightforward.

The present-day structure of the field is the result of a complex tectonic evolution where different deformation events superimposed through time: Mesozoic extension, Late Paleogene uplift, Pliocene - Early Pleistocene traspression, Middle-Late Pleistocene – recent extension. This last event is represented by two NW-SE extensional to transtensional fault trends, East Agri Fault System (EAFS) and Monti della Maddalena Fault System (MMFS) dissecting the allochthonous complex. These two fault sets do not propagate into the reservoir where faults are still preserving reverse displacement.

This work aims to characterize the fault framework and structural evolution of Apulian Platform within the Agri oil field by means of well data analysis and seismic interpretation of the latest reprocessed 3D seismic volume. In detail, three main faults sets have been recognised, showing multiple reactivation: NW-SE WNW-ESE and NNE-SSW oriented. These faults play a role during the Cretaceous extensional phase, the Late Paleogene tilting and erosion distribution and finally the Pleistocene transpression which determines the pop-up generation and present-day configuration.

Collision of Northern Apennines with Southern Alps and the origin of the Bobbio Tectonic Window: Evidence from a regional cross-section connecting the outcropping and buried thrusts

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Keywords: Bobbio Window, Northern Apennines, structural geology.

The Plio-Pleistocene evolution of the Northern Apennines fold-and-thrust belt is characterized by the prolonged interaction between the outermost thrusts of the Emilian Arc, and the buried thrusts of the Southern Alps. More specifically, the development of the Emilian Arc is associated with the emplacement of the Norther Apennines on a foreland area where inherited structural highs control the presence or absence of the units hosting the main Oligo-Miocene detachments.

Earlier studies explain that the structural block of the Southern Alps hinders the northward propagation of the Emilian Arc. In areas where the outer thrusts can no longer accommodate additional deformation, older thrusts are reactivated. This process leads to out-of-sequence deformation and facilitates uplift in the inner sections of the arcs.

A detailed analysis of an extensive database of seismic reflection profiles and wellbore information has been conducted to propose that the out-of-sequence deformation in the Emilian Arc has been active since the Pliocene and this interpretation opens the question of whether the reactivation of the older thrusts occurred also in the outcropping thrusts of the innermost part of the Northern Apennines. Current works are conducting apatite (U-Th)/He low-T thermochronology in sandstones from the San Salvatore Fm, at the core of the Bobbio Tectonic Window, localized directly to the south of the major zone of interaction between the two studied chains. Preliminary thermochronological results from the Bobbio Tectonic Window show a Pliocene cooling signal between ca. 2 and 4 Ma, evidencing that a reactivation of the main thrusts could be the cause for this uplift during the Pliocene.

To integrate the analysis and to give a subsequent explanation of the origin of the Bobbio tectonic window, we constructed a regional cross-section merging the surface geology from the Bobbio and Ponte dell'Oglio CARG sheets with subsurface information from a regional 2D seismic line across the Po Plain, intersecting the main thrusts of the buried Emilian Arc and Southern Alps thrust front. This new cross-section provides a better understanding of the relationship between the outermost thrusts in the Po Plain and the ones outcropping in the Bobbio Tectonic Window.

The multi-Ma history of the Fucino extensional basin inferred from the stratigraphy of a deep borehole in the Avezzano town (Central Apennines)

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Keywords: Central Apennines, borehole multimethod stratigraphy, post-orogenic extension.

A 271 m-deep geognostic borehole was drilled within the town of Avezzano (Fucino Basin, central Italy) as part of the "Level 3" seismic microzonation investigations of the Municipality of Avezzano. The town is located near the NW margin of the Fucino Basin, a post-orogenic extensional basin in the core of the central Apennines, which developed in the hanging wall of a still active normal fault system. Seismic reflection data published since the early 2000s show a semi-graben geometry, with a wedge-shaped sedimentary infill thickening towards the East, atop a main SW-dipping normal fault. The borehole crossed the western, thinner sector of the sedimentary wedge.

The primary aim of the drilling was to reach the geological bedrock, initially estimated by geophysics to lie at a depth of 150–160 m. From the surface to approximately 140 m depth, a continuous and well-preserved succession of lacustrine deposits was cored. Between 140 and 186 m, core recovery was discontinuous and the sediments remain indicative of a low-energy lacustrine environment, interbedded with coarser layers. Below 186 m, core recovery was extremely difficult, likely due to the presence of predominantly coarse-grained deposits. At 255 m, a sample of continental clay was recovered. From 269.5 to 271 m, a core of overconsolidated clays was recovered, with thin sandy interbeds, well-stratified, with bedding planes dipping approximately 45°, suggesting a flysch-like geological bedrock.

Nine tephra layers were identified within the uppermost 40 meters, three of which were numerically dated. Samples of the lacustrine sequence were obtained every ~10 cm, and resolution was increased (samples every 2 cm) at some levels for paleomagnetic and palynologic analyses. Magnetic susceptibility was measured at 2 cm resolution. The integrated lithologic, tephrostratigraphic, paleomagnetic, and palynologic analyses are discussed to develop a chronostratigraphic model of the sedimentary infill, with implications for the late- and post-orogenic evolution of the central Apennines. Micropaleontological analyses of the bedrock core give insights for bracketing the age of the transition from compressional tectonics to post-orogenic extension.

3D Structural Model of the Marche Offshore based on geological and geophysical data: the geometry of the Tamara and Cornelia Structures

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Keywords: 3D structural modeling, Northen Apennines front, fault geometry.

The northern sector of the Marche offshore represents a crucial area for analyzing active structures related to the Northern Apennines front, as well as an ideal testing ground for integrating historical datasets and three-dimensional geophysical data.

In this work, we present a structural interpretation and a high-resolution 3D geological model of the Pesaro offshore, focusing on the Tamara and Cornelia structures, located in the frontal zone of the Northern Apennines. This study was conducted within the framework of the SPIN project (*Test delle buone pratiche per lo Studio della Potenziale INterazione tra attività offshore e pericolosità naturali* - Best practice testing for the Study of Potential INteractions between offshore activities and natural hazards), coordinated by INGV.

The analysis was carried out by integrating various data types, including publicly available data and, primarily, confidential 2D and 3D seismic surveys and well-log data granted by ENI S.p.A., as well as geological maps and technical reports. Check-shot and well-velocity data were analyzed to estimate the interval velocities of each stratigraphic unit, allowing the development of a refined 3D velocity model at a regional scale. By integrating this information, we were able to run a robust depth conversion and reconstruct the geometries of the tectonic structures shaping the area. The 3D structural model of the upper crust has been extended deep to approximately 50 km depth by integrating tomographic published studies and geodynamic reconstruction at the crustal scale.

The reconstructed geometries suggest that the recent and present-day deformation is controlled by the interaction between inherited Mesozoic structures and the Apennine-related contractional faults. These interactions have favored the growth of the Tamara and Cornelia folds, resulting in the segmentation of the Northern Apennines thrust front.

The 3D model obtained not only clarifies these local-scale geometries but also allows for the investigation of the seismogenic potential of these structures, which were deemed to be the causative faults of the November 2022 earthquake sequence (Mw 5.5).

This study highlights how the integration of multidisciplinary datasets into a high-resolution 3D structural model allows for a clearer definition of the geometry and kinematics of buried thrust-related structures, providing a robust framework for future seismotectonic analyses and geodynamic interpretations of the Northern Apennines front.

Thrust inversion during post-orogenic extension: new insights from the Monte Soratte thrust, Central Apennines (Italy)

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Keywords: inverted thrust, reactivated fault, deformation mechanism.

The Apennine chain records a long-lasting and polyphasic tectonic history starting from the Miocene, encompassing an initial tectonic shortening accommodated by NE-wards propagating thrusts, followed by a regional Late Pliocene-Quaternary extensional phase. Many works emphasize how some Apennine tectonic structures were able to accommodate both compression and extension at different times. This interplay is promoted when the inherited compressional structures are favorably oriented with respect to later extensional stresses. In such cases, thrust planes may be reactivated as normal faults, adding structural complexity in tectonic reconstructions due to the progressive overprint and obliteration of earlier compressional structures by the subsequent extensional phase. These tectonic interactions considerably challenge the understanding and reconstruction of the intricate tectonic history of the orogen structural evolution. To better understand these processes, attention must be paid to key sectors of the Apennine chain, which are essential for understanding the through time and space deformation migration and evolution.

This work focuses on the Monte Soratte structure, located in the internal sector of the Central Apennines (central Italy). This isolated carbonate ridge occupies a key structural position and may provide crucial insights into the broader evolution of the Apennine chain.

We present preliminary structural results from the Monte Soratte thrust, which juxtaposed the carbonates of the Corniola Fm onto the "calcari nodulari dell'Infernaccio" and Calcare Massiccio units, and mainly developed within the phyllosilicate-rich and weak lithotype Scaglia Variegata Fm. The main thrust zone is composed of up to 10 m-thick SW-dipping SC-C' compressional domains (D_1), with a top-to-the NE tectonic transport, constrained by lineated tectonic carbonates and sigmoidal clasts embedded within the foliation. Locally, these domains are crosscut by a later SC fabric, associated with top-to-the SW extensional kinematics (D_2), which partially obliterate the D_1 domains, yielding to a late reactivation of the thrust zone during post-orogenic extension.

Our data highlights the crucial role of rheological contrast between the different lithologies involved in the deformation, where the phyllosilicate-rich Scaglia Variegata Fm was able to i) localise deformation during the Miocene compression (D_1) and ii) be tectonically inverted as an extensional fault zone during the post-orogenic extensional phase. The still partially hidden Monte Soratte history thus provides important insights into fault reactivation processes and the importance of structural/stratigraphical inheritance in shaping the central Apennine chain. Further studies will comprise detailed U-Pb carbonate dating and C-O isotope systematics on the syn-kinematic structures, to constrain the deformation timing and the fluid signatures associated with D_1 and D_2 tectonic phases.

Neogene non-cylindrical kinematic evolution of the Southern Apennines orogen, Italy: insights from the southern Lucania region

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Keywords: fold and thrust belt, kinematic evolution, Southern Apennines.

Neogene deformation in the Southern Apennines fold and thrust belt affected paleogeographic domains with different mechanical stratigraphy and built up an orogen involving two crustal levels with dissimilar structural styles. The upper level (Apennine belt) includes detached thrust sheets formed at the expanses of both basinal (Ligurian Ocean and Lagonegro or Lagonegro-Molise Basin domains) and shallow-water rocks (Apenninic Platform domain) deposited on the western margin of the Adria continental plate. The lower orogenic level (Apulian belt) is formed by a thicker carbonate platform succession that represents the buried western extension of the Apulian foreland located to the east of the Apennines. A detailed geological and structural analysis integrated with seismic profiles and well-log interpretation in the southern Lucanian segment of the orogen (Mt. Alpi-Mt. Raparo area) allowed to reconstruct multiple phases of non-cylindrical deformation that led to the assembly of the two superposed orogenic levels. The structural fabric was restored for documented paleomagnetic rotations allowing the construction of a kinematic model for this segment of the Southern Apennines. The first deformation is represented by extensional faults that formed within both the Apenninic Platform, Lagonegro Basin and Apulian Platform rocks before their involvement in the fold and thrust belt, possibly during a forebulge stretching stage. The ensuing orogenic contraction is marked by development of thrusts and folds that are associated with the early-middle Miocene south-directed stacking of the Liguride, Apenninic Platform, and Lagonegro thrust sheets. During the late Miocene-early Pliocene a change in orogenic vergence to the east-southeast and then to the east-northeast occurred when the allochthonous stack overrode the western part of the Apulian Platform. Starting from the early Pliocene, shortening affected the buried Apulian Platform developing broad antiformal highs that passively involved the overlying allochthonous wedge. Because of contractional uplift, south-southeast-displacing low-angle normal faults dismembered the thrust stack and caused a severe thinning of the orogenic pile. Between the late Pliocene and the Pleistocene, high-angle reverse and transpressional faults encroached the Mt. Alpi Unit, the only section of the Apulian Platform exposed in the Apennines, which was uplifted more than 5 km. The concurrence of non-coaxial contractional phases and of both pre-orogenic and synorogenic extension episodes documented here explains the complex structural arrangement of tectonic units observed in the area, which is difficult to reconcile in the context of a steady cylindrical deformation as often assumed for the Apennines.

Late Paleogene volcaniclastic turbidite succession of the Candela Stream (Southern Italy). New constrains for the evolution of the Southern Apennine in the Central Mediterranean

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Keywords: volcaniclastic turbidites, U-Pb zircon ages, late Paleogene.

Recent multidisciplinary re-examinations of a volcaniclastic turbidite succession—traditionally referred to as the Tufiti di Tusa Formation and exposed along the Candela Stream, near the Calabria-Basilicata boundary in Southern Italy—have provided further insights into sediment provenance, transport pathways, and paleogeography of the depositional basin.

The succession comprises three informal lithostratigraphic units (Gallicchio et al., 2023), arranged from bottom to top as follows:

(i) Unit I, characterized by calciclastic arenaceous turbidites with a minor siliciclastic components;
(ii) Unit II, dominated by siliciclastic arenaceous turbidites with occasional calciclastic intercalations;
(iii) Unit III, primarily composed of volcaniclastic gravity-flow deposits.

Petrographic analysis, supported by geochemical data, reveals clear temporal variations in detrital input. The samples belong to three distinct petrofacies, reflecting differences in both composition and grain size.

Unit I sandstones range from fine- to coarse-grained and contain calcitic fossils and carbonate cement. The silicate fraction includes quartz, K-feldspar, and mica, along with plutonic fragments and metamorphic clasts (e.g., quartzites, schists, and gneisses). Ophiolitic lithics bearing garnet and epidote are also locally present.

Unit II sandstones are medium- to coarse-grained and predominantly siliciclastic, with minor bioclastic content. While the mineralogical assemblage resembles that of Unit I, there is an increased abundance of micaschist and ophiolitic clasts. Volcanic lithics appear sporadically in the upper part of this unit. In contrast, Unit III sandstones are dominated by volcaniclastic material. Porphyritic andesite lithics constitute approximately 70% of the framework and are characterized by idiomorphic phenocrysts of plagioclase, pyroxene, amphibole, and biotite set in a strongly altered groundmass. Minor components include plutonic, metamorphic, and carbonate fragments. Among the metamorphic lithics, garnet-, glaucophane-, and muscovite-bearing gneisses, are predominant. Geochemical data corroborate the petrographic observations, with mafic element concentrations increasing upward from Unit I to Unit III.

U-Pb zircon dating from detrital euhedral grains in syn-sedimentary volcaniclastic sandstones of Unit III yields ages around 33±1 Ma (Fornelli et al., 2020). These late Eocene-early Oligocene ages are further supported by calcareous nannofossil biostratigraphy. New U-Pb data on zircons (159 ages) from sandstones in Units I and II indicate that the lower and middle parts of the succession contain Precambrian (4180 - 542 Ma n = 90), Cambrian (538-505 n = 7), Ordovician-Silurian (484-419 n = 11), Devonian (412-368 n =1 0), and Carboniferous- Permian (340-254 n = 13) zircon ages. In the upper part of Unit II, Triassic–Jurassic (246-158 Ma, n = 14) and additional younger ages ranging from 136 to 41 Ma (n = 14) are also recorded.

Fornelli A. et al. (2020) - Preliminary U-Pb detrital zircon age from Tufiti di Tusa Formation (Lucanian Apennines, Southern Italy): evidence of Rupelian volcaniclastic supply. Minerals, 10, https://doi.org/10.3390/min10090786.

Gallicchio S. et al. (2023) - Depositional record of confined turbidites in syn-subduction intraslope basin: insight from the Tufiti di Tusa Formation (Southern Apennines, Italy). Mar. Petrol. Geol., 147, https://doi.org/10.1016/j.marpetgeo.2022.105969.

Provenance and Source to Sink of the Middle – Late Jurassic successions of the External Rif basin (Rif chain, Morocco): Evidence from sedimentary petrology and detrital Zircon geochronology

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Keywords: U-Pb geochronology, , provenance, External Rif Chain.

This study deals with the provenance of the Middle-Upper Jurassic sedimentary successions of the Mesorif and Intrarif basin belonging to the External Domain of the Rif Chain, by merging sedimentary petrology and U-Pb zircon geochronology. Nineteen thin sections and fifteen marl/clay samples were collected from five different stratigraphic sections which are: Jbel Izzarene, Jbel Tabouda, Marticha, Jbel Taineste, and Jbel Aouzai. We performed modal petrography, U-Pb Geochronology, and Geochemical analysis for sandstones and mudrocks respectively, using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), and X-Ray Fluorescent (XRF) facilities.

According to the mineralogical content, the Middle-Upper Jurassic Sandstone suites are Quartz-arenite, Sub-arkose and Sub-litharenite. Detrital sandstone modes reveal provenance from Craton interior, Recycled orogen. They also indicate primary multi-source known as magmatic felsic and middle to high-rank metamorphic rocks sources provenances. The elemental geochemistry supports a mixed source provenance reported from detrital modal analysis, as evidenced by several geochemical proxies such as Th/Co, Th/Sc, La/Sc, Th/Cr, Cr/Th ratios, and V-Ni-La*10 and V-Ni-La*4 ternary plots.

The U-Pb detrital Zircon geochronology of these suites reveals five main age clusters suggesting potential source areas: Archean, Paleoproterozoic, Mesoproterozoic, Neoproterozoic, and Paleozoic ages. The U-Pb Zircon ages may suggest detrital Zircons were supplied from culminant mounts of Eburnean and Cadomian/Pan-African orogens, including the Moroccan Meseta, High Atlas, Anti Atlas chain, and Western African craton. However, the Hoggar Mountains as an additional potential source area cannot be excluded.

Linkage between surface and tectonic processes through multiple spatial scales: form Mediterranean to the Apennines

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Keywords: Mediterranean, Apennines, deformation.

The Mediterranean formed through the subduction of the Tethyan Ocean beneath the southern margin of the Eurasian plate. Within this complex tectonic framework, the Apennines represent a subducting orogen that developed following the migration of the trench–arc–back-arc system across the western and central Mediterranean. To better understand the interaction between surface processes and tectonic forces in shaping orogenic belts, we investigate the relationships among morphometric characteristics, exhumation, and crustal deformation across the Mediterranean region, with a particular focus on the Italian Apennines.

At the scale of the Mediterranean, we converted over 7,300 published thermochronological cooling ages into exhumation rates and integrated them into a plate tectonic reconstruction using available kinematic data. For multiple tectonic blocks, we compared exhumation rates with convergence velocities, eustatic sea-level curves, and climatic temperature trends to identify potential common controls. Our results show asynchronous exhumation across different tectonic domains, suggesting that exhumation is primarily governed by local (i.e., orogen-scale) rather than regional processes (i.e. climate). At the scale of the Apennine belt, a detailed analysis integrating morphometric data with crustal and Moho structure reveals a strong coupling between surface topography and deeper architecture. This coupling is expressed as a marked asymmetry in the Northern Apennines, contrasting with a more symmetric configuration in the Central and Southern segments.

In conclusion, our study demonstrates that tectonic processes, including subduction, collision, and trench retreat-driven extension, are key drivers of topographic uplift, erosion, and exhumation across the Mediterranean. The positive correlation between exhumation rates and tectonic deformation highlights the dominant role of geodynamic processes in shaping the orogens. At more localized scales, as in the Apennines, topographic and structural patterns closely resemble the geometry of the Moho, underscoring the influence of deep dynamics. Finally, we identify notable along-strike variations within the Apennines, suggesting the presence of distinct, potentially ongoing geodynamic mechanisms even within a single orogenic system.

Tectono-Sedimentary Evolution of wedge-top basins and implications for paleo-carbon sequestration: insights from the Nebrodi Mountains (Sicily)

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Keywords: wedge-top basins, organic carbon sequestration, Sicily.

Wedge-top basins, developing during mountain building, are key settings to investigate the interplay between tectonics, sedimentation, and organic matter preservation. These basins typically form under compressional to post-collisional regimes, where active subsidence, rapid sediment supply from uplifting orogenic fronts, and variable paleogeographic and climatic conditions combine to create environments prone to organic-rich deposition. In particular, high sedimentation rates, restricted circulation, and periodic anoxia can enhance organic matter accumulation and preservation, making these basins significant for paleoenvironmental and paleoclimatic reconstructions.

This contribution focuses on wedge-top basins of the Nebrodi Mountains (northern Sicily), analyzing their tectono-sedimentary evolution with emphasis on organic matter accumulation and preservation. These basins, developed in Nebrodi Mountains in the Apenninic-Maghrebian fold-and-thrust belt in the area from Caronia to Troina towns, exceptionally preserve sedimentary successions that record syn- to post-orogenic stratigraphic signals. Stratigraphic, sedimentological and structural data, together with organic petrography and geochemistry, sandstone provenance studies, reveal the influence of tectonic activity, basin subsidence, sediment supply, and environmental/climatic conditions controlling distribution and preservation of organic-rich facies.

The Nebrodi case study highlights how wedge-top basins offer effective conditions for paleo-carbon sequestration. Understanding these controls is crucial for reconstructing basin evolution vs. carbon sequestration in present-day analogs.

Tracing the Northern Apennine interplate shear zone in the Tuscan Apennine: first evidences from the Florence and Chianti mountains areas

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Keywords: tectonic mélange, accretionary prism, Subligurian units.

In the Northern Apennines, remnants of the Cretaceous–Eocene accretionary prism – comprising the Ligurian and Subligurian Units derived from oceanic to ocean-continent transition domains and their sedimentary cover (Epiligurian and epi-Subligurian successions) – overthrust Oligocene-Miocene foredeep wedges deposited on the Tuscan-Umbria continental domain. The shear zone marking this tectonic superposition varies along strike. In the southeastern Emilia Apennines, it consists of a tectonic mélange containing blocks sourced from the Ligurian, Subligurian, and Epiligurian units (Sestola-Vidiciatico Unit), while to the northwest, it transitions into coherent tectonic slices of Subligurian units. Both the Sestola-Vidiciatico tectonic mélange (Remitti et al., 2012) and the Subligurian units have been interpreted as exhumed segments of the Apennine plate interface active during the Miocene (Vannucchi et al., 2008, 2012).

The continuation of this shear zone into the Tuscan Apennines has remained enigmatic. Although Subligurian Units occur between Ligurian and Tuscan Units in this sector – mirroring their arrangement in the northwestern Emilia Apennines – their relationship to the plate interface has been unclear, and an upper-plate position could not be ruled out. Notably, no tectonic mélange had been identified in this structural position in the Tuscan Apennines until our recent mapping work.

As part of the Italy's National Geological Mapping Project (CARG Project), we have identified a tectonic mélange between Ligurian Units and Tuscan Domain foredeep deposits in the Florence area. This mélange primarily consists of pervasively deformed shale-limestone alternations displaying characteristic block-in-matrix fabric and scaly cleavage, with unrooted fold hinges and boudinage of the competent limestone layers, while primary stratification is rarely preserved. This chaotic assemblage incorporates meter- to kilometer-scale coherent blocks of marly-calcareous successions, siliciclastic sandstones, litharenites, and silty marlstones, along with deformed clayey mass transport deposits (olistostromes) and ophiolite-bearing breccias. The mélange components and their ages show affinities with both Ligurian/Subligurian units and the Epiligurian succession. Laterally, the mélange transitions into discontinuous, lozenge-shaped slices of Subligurian units, ranging from tens of meters in the Chianti Mountains to kilometer-scale near Florence.

These new findings – including mélange mapping, dating of incorporated materials, and structural analysis – provide critical constraints on the evolution of the plate interface in the inner Northern Apennines during the Oligocene-Miocene period, helping to resolve a long-standing gap in our understanding of this tectonic boundary.

Remitti F. et al. (2012) - Deformation, fluid flow, and mass transfer in the forearc of convergent margins: A two-day field trip in an ancient and exhumed erosive convergent margin in the Northern Apennines. In: Vannucchi, P. & Fisher, D. (Eds.), Deformation, Fluid Flow, and Mass Transfer in the Forearc of Convergent Margins: Field Guides to the Northern Apennines in Emilia and in the Apuan Alps (Italy). Geological Society of America Field Guide, 28, 1-34, https://doi.org/10.1130/2012.0028(01).

Vannucchi P. et al. (2008) - Geological record of fluid flow and seismogenesis along an erosive subducting plate boundary. Nature, 451, 699-703, https://doi.org/10.1038/nature06486.

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Tectonic evolution of the allochthonous units exposed in the Monti di Lauria area (Southern Apennine, Italy): evidence for low-angle normal faulting

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Keywords: Southern Apennines, geological-structural survey, geological map.

The Apennine fold and thrust belt (ftb) shows in its current configuration the result of tectonic events that have been recorded in geological structures over time. The Lauria Mountains Ridge (LMR) (Basilicata), separating the deeper tectonic units of the Southern Apennines exposed in the Monte Alpi and the Sirino areas, from the shallower section of the tectonic pile making up the Pollino Massif, represents a significant area for studying the tectonic evolution of the fold and thrust belt. In addition, the LMR contains important groundwater reserves, whose management requires a detailed knowledge of the structural setting of the carbonate aquifers.

To achieve the aforementioned goals, a geological-structural survey, funded by project Tech4You (Directorial Decree n.2021/3277-n.ECS0000009), was carried out in an area of about 100 km^2, between Castelluccio and Lauria, where lithotypes and tectonic structures were mapped, paying particular attention to the arrangement of rock bodies and the relationships between tectonic units. A careful sampling of the carbonate rocks was carried out in order to identify their age, allowing a better understanding of the structural relationships between geological units.

The LMR is characterized by a nearly complete section of the tectonic units of the Southern Apennines, which include, from bottom to top: i) the deep-sea Lagonegro Units; ii) the carbonates of the Apennine Platform and iii) the deep-sea Sicilide and Liguride Units, locally overprinted by very low-grade metamorphism. In the northern sector of the area, the Sicilide and Liguride Units are directly superimposed on the Lagonegro Units. The latter are affected by a large-scale overturned fold displaying similar orientation with respect to folds occurring in the nearby Sirino area.

The Apennine Platform carbonates are represented by Triassic Dolomites and Jurassic to Eocene Limestones, covered by carbonate and siliciclastic of lower Miocene age. Within the Apennine Platform, structural relationships suggest that the major carbonate bodies are separated by low-angle normal contacts well exposed in the area of La Zaccana Mt. Here, low-angle tectonic contacts mainly separate Triassic dolostones at the footwall and Jurassic to Cretaceous limestones at the hangingwall. This allows to consider the aforementioned carbonates belonging to a single tectonic unit later dissected by low-angle normal faults. In the same area, several low-angle faults, with dip-slip kinematics and average dip to the NE, are observed at the contact between platform carbonates and the Liguride Units above (Mazzoli et al., 2014). Fault planes are wavy, often discontinuous and sometimes cut by high-angle faults. The tectonic complexity of the study area is enhanced by the presence of different sets of medium to high-angle faults that cover a high range of orientations. This indicates that the allochthonous units were affected by intense polyphase extensional tectonics after their stacking.

Mazzoli S. et al. (2014) - Low-angle normal faulting and focused exhumation associated with late Pliocene change in tectonic style in the southern Apennines (Italy), Tectonics, 33, 1802-1818, https://doi.org/10.1002/2014TC003608.

The enigma of the eurites clast in the Messinian deposits of the Tuscany

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Keywords: sediment provenance, messinian conglomerates, Apennine.

According to legend, during the quest for the Golden Fleece, Jason and the Argonauts landed on a beach of Elba Island to rest, using white, porous pebbles to wipe away their sweat. Allegedly, traces of sweat permanently stained these rocks with blue and black hues. While the legend is purely anecdotal, the true mystery of the eurites—acidic dike rocks characterized by blue tourmaline phenocrysts—lies not in their origin, but in their presence within Messinian fluvial deposits of the Volterra Basin, located in inland Tuscany, approximately 100 km from the only known outcrops of eurites on Elba Island and surrounding.

The occurrence of eurite clasts in the Messinian deposits of the Volterra Basin has previously been the focus of multiple studies (Ref; Ref). In this study, we present the results of a multidisciplinary investigation integrating heavy mineral analysis, sediment characterization, and depositional architecture assessment using photogrammetric techniques. Our goal is to refine constraints on the provenance and sedimentological context of these Messinian deposits.

The selected outcrop, located at La Pertica near the village of Larderello, provides the most comprehensive exposure of late Messinian conglomerates within the basin. A 3D photogrammetric model of the outcrop reveals a depositional architecture dominated by thick, stratified, clast-supported conglomerates interbedded with sandy layers indicative of fluvial channels. The observed sedimentary architecture is consistent with high-energy, braided fluvial systems transporting coarse clastic material. Paleocurrent indicators (imbricated gravels) suggest a general flow direction from south to north.

Heavy mineral assemblages were analysed via Raman spectroscopy on two samples from the sandy interbeds. The detection of significant amounts of brookite—a polymorph of titanium dioxide—supports a provenance from Elba Island, where this mineral is known to occur.

Our results support the existence of an active fluvial system during the late Messinian capable of transporting gravels and sands from the Elba Island region toward the east and northeast into the Volterra Basin, as suggested by previous studies . The paleogeographic implications are substantial: not only was Elba Island topographically connected to central Tuscany during the Messinian, but the presence of an eastward-flowing, high-energy fluvial system implies that the Apenninic drainage divide may have been located near the present-day position of Elba Island—an interpretation warranting further investigation.

Pandeli E. et al. (2010) - New data on the paleogeography of Southern Tuscany (Italy) since Late Miocene time. International Journal of Earth Sciences, 99.

Pascucci V. et al. (2006) - Veally formation and filling in response to Neogene magmatic doming of Elba Island, Tuscany, Italy. In: Dalrymple R. W., Leckie D.A., Tillman R. W. (Eds), Incised Valleys in Time and Space, SEPM Special Publication.

Source-to-sink variations in the Oldman Formation (Campanian, Belly River Group) at the U.S.- Canada border

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Keywords: non-marine deposits, retrogradational-progradational pattern, petrographic analysis.

The Oldman Formation is the middle unit of the non-marine Belly River Group, deposited from ~ 77.5 and ~ 75.5 Mya (Campanian, Upper Cretaceous) and is widely exposed in the southern plains of Alberta (Canada). This clastic, alluvial unit is renowned for its rich and diverse fossil fauna and has been the subject of multiple studies focusing on source-to-sink relationships during large-scale transgressive-regressive events. This work investigates nine newly acquired stratigraphic sections representative of the lower 80 meters of the Oldman Fm. in the Milk River Valley drainage system. Measured sections extend from the Taber Coal Zone (TCz) - which marks the base of the Oldman Fm. - to the 'Comrey sandstone', a sand-dominated interval associated in literature to the maximum basinward progradation of the Belly River Group. Sandstones representative of the TCz-Comrey interval indicate an overall trend toward quartz-enriched sandstones: this trend changes in the Comrey member, where quartz clasts abruptly decrease to ~ 40%, and ~15% of clasts are represented by olivine, not present in the lower Oldman beds. Petrographic analysis also led to the identification of a previously unmapped stratigraphic interval characterized by highly cemented, white arenites, nicknamed 'Big White', classified as a quartz arenite. Petrographic data suggests three different sediment source areas during the deposition of the lower Oldman Formation and therefore a more complex source-to-sink relationship for the basal beds of this unit known in literature until now.

Further, lithostratigraphic and petrographic data allow to discriminate three different depositional sequences of 3rd order, where the first two presented a retrogradational and consequent progradational pattern. We demonstrate a higher sedimentary cyclicity than previously thought, most likely linked to changes in sediment source areas, as evidenced by petrographic data. High frequency depositional cycles delimited by subaerial surfaces change current understanding of the processes leading to the deposition of the Oldman Formation.

Unveiling the Bobbio Tectonic Window: thermo-tectonic investigation of the Alps-Apennines junction

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Keywords: Northern Apennines, low-temperature thermochronology, buried thrust front.

The dynamic relationships between the S-verging Southern Alps and the NE-verging Northen Apennines fold-and-thrust belts and their shared Po Plain foreland basin, including their kinematic interactions, represent a classic and still debated problem. In this context, the regional transect going from the Bobbio Tectonic Window (BTW) in the Emilian Apennines, where Miocene foredeep turbidites crop out, to the central Po Plain subsurface, where the Northern Apennines thrust front along the Emilian Arc interferes with the Southern Alps orogenic front, represents a key point for detecting these relationships. Existing studies have focused on fault slip-rate reconstructions based on the interpretation of seismic lines along the Emilian arc, but a comprehensive tectonic reconstruction including thermochronological investigation of the turbiditic sequence of the BTW is still lacking. In this work, we aim to understand the relationship between BTW development and the propagation of the Northern Apennines and Southern Alps buried thrust fronts. In particular, we analysed the cooling/exhumation history of rocks exposed at the core of the BTW together with the slip-rate history of the Northern Apennines thrust front along the Emilian Arc. We apply apatite fission-track (AFT) and (U-Th)/He low-T thermochronology analysis to BTW samples of the San Salvatore Fm. spanning in age between 20 and 16 Ma (Lower-Middle Miocene). Our preliminary thermochronological results from the BTW show a Pliocene cooling signal between ca. 2 and 4 Ma and a maximum T of ca. 90°C. We interpret these results as the signal of an out-of-sequence thrusting reactivation within the inner Northern Apennine fold-and-thrust belt due to the interaction between the frontal part of the Emilian Arc with the Southern Alps. This study shows how far field geological structures can influence the kinematics of thrust systems and helps to explain the generally decreasing Pliocene-Pleistocene tectonic activity of the Northern Apennines buried thrust front.

Evolution of the Transantarctic Basin in Victoria Land (Antarctica): insights from quantitative sandstone petrography

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Keywords: Antarctica, sandstone petrography, Gondwana.

Sedimentary clastic sequence analysis is a fundamental tool to understand the Earth plate dynamics, because the sequences record variations in the depositional environments and basin morphology settings. In the Late Paleozoic and Mesozoic, the Antarctic region occupied the paleo-Pacific margin of southern Gondwana. Since Permian, the paleo-Pacific plate subducted under Gondwana leading to the development of a magmatic arc (i.e., the Gondwanide Orogen). In the forearc and retroarc position developed sedimentary basins that recorded this evolution. The Beacon Supergroup represents the sedimentary filling of the Transantarctic Basin, a basin located in the retroarc setting. These poorly deformed sedimentary sequences, mainly fluvial sandstones and mudstones, currently crop out along the Transantarctic Mountains. The deposition of the Beacon Supergroup lasted more than 200 Myr (Devonian to Early Jurassic) in Victoria Land and nearby territories, recording crucial events in the history of the Earth. The composition of the Beacon Supergroup sandstones was found to be correlated with major tectonic processes in response to subduction dynamics, which ultimately conditioned the source-to-sink system and provenance imprints. Petrographic variability in sandstone composition is tracked through space and time by a quantitative analysis of all available published data and new updated ones, from Transantarctic Mountains and Tasmania. The variability of grain composition detected by quantitative sandstone petrography reveals that the Victoria Land sector transitioned from an intracratonic basin in back-bulge position to foredeep basin setting.

S13.

The role of CARG project as an indispensable tool for advancing Geoscience

CONVENERS AND CHAIRPERSONS

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Geological Mapping of the Siliciclastic Syn-orogenic Deposits of the 390–Frosinone Sheet (CARG Project): preliminary results

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Keywords: geological mapping, syn-orogenic deposits, CARG Project.

As part of the geological survey of the 390-Frosinone Sheet (CARG Project), we present the preliminary results of the mapping of the Upper Miocene terrigenous deposits, which are extensively outcropping. The mapped area belongs to the Valle Latina and the Ernici Mountains, where foredeep and wedge-top deposits mark the involvement of the region into the orogenic system.

In the Valle Latina, the pre-orogenic deposits include the Calcari a Radiolitidi (RTD, Upper Cretaceous p.p.), the Calcari a Briozoi e Litotamni (CBZ, Lower-Middle Miocene), and the Marne and Argille a Orbulina (UAM, Upper Miocene p.p.). The overlying syn-orogenic deposits include the Frosinone Fm (FFS, Upper Miocene p.p.), which is poorly exposed and laterally discontinuous, and the Arenarie di Torrice (TCE, Upper Miocene p.p.). The Frosinone Fm is characterized by siliciclastic turbidites dominantly composed of pelitic–arenaceous facies association (FFSc) and, secondarily, arenaceous–pelitic facies association (FFSb). The Frosinone Fm was deposited in the late Tortonian foredeep domain of the central Apennine orogenic system (Cipollari & Cosentino, 1993, and references therein). The Arenarie di Torrice overlie the Frosinone Fm. unconformably; they consist of massive sandstones, sometimes interbedded with clays. TCE was deposited in a wedge-top basin during the early Messinian. Although the stratigraphic relationship between FFS and TCE is not observable in many areas, in selected localities it is well exposed, showing the unconformity between the Arenarie di Torrice (TCE) and the Frosinone Fm (FFS).

To refine the age of both FFS and TCE, a biostratigraphic analysis of the calcareous nannofossils is in progress. Preliminary results point to the presence of 5-rayed discoasters in the pelitic beds of FFSc and the occurrence of *Amaurolithus primus* in the clay horizons of TCE. Different particle size and composition for the FFS and TCE sandstones have been suggested by previous studies (La Monica, 1966). To investigate such differences, petrographic analyses are also underway.

Cipollari P. & Cosentino D. (1993) - Le "Arenarie di Torrice"; Un deposito di bacino di piggy-back del Messiniano nell'Appennino centrale. Italian Journal of Geosciences, 112(2), 497-505.

La Monica G.B. (1966) - Caratteristiche granulometriche e sedimentologiche delle arenarie di Torrice (Frosinone-Lazio meridionale). Atti Acc. Gioenia Sc. Nat., 18, 285-312.

Stratigraphy of the Dolomites at the CPE revealed by geological mapping of the CARG Project

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Keywords: Heiligkreuz, CARG, Dolomites.

The Heiligkreuz Formation (HKS) is an Upper Triassic lithostratigraphic unit that flattened an articulated paleotopography by filling deep basins between the lower Carnian carbonate platforms of the Southern Alps, particularly the Dolomites region. Within the stratigraphic succession, the HKS sits on the Dolomia Cassiana (DCS), or its laterally equivalent basinal deposits (San Cassiano Formation, SCS), and lies below the Travenanzes Formation (TVZ). It predates the establishment of the vast tidal flat system of the Dolomia Principale (DPR).

Furthermore, the HKS recorded the carbon cycle perturbations associated with the Carnian Pluvial Episode (CPE), which resulted in the crisis and demise of microbial carbonate platforms (DCS), then replaced by oolitic and skeletal systems. It includes sandstones which testify to the increase in immature terrigenous input, due to intensification of the hydrogeological cycle. This translated into a wide variety of lithofacies within the HKS. Notably, the formation preserves a complete depositional sequence with forced regressive (FSST), lowstand (LST), transgressive (TST), and highstand (HST) systems tracts.

The Heiligkreuz Formation was formalized on Sheet 029 “Cortina” (Neri et al., 2007). There, a subdivision into three members (from bottom to top: Borca Member HKS1, Dibona Sandstone Member HKS2, and Lagazuoi Member HKS3) was proposed, while two additional members (Alpe di Specie Member HKS4 and Dürrenstein Member HKS5) were later added on Sheet 016 “Dobbiaco” (Gianolla et al., 2018). The Alpe di Specie Member is a predominantly clay-rich terrigenous unit that was identified in basin areas. This member is characterized by the absence of the typical calciturbidites that record the downslope export from productive Cassian carbonate platforms (DCS). It appears in the field as a variant of the San Cassiano Formation (SCS) which lacks calciturbidites, and it was in fact attributed to SCS in many previous sheets. However, SCS is by definition a lithostratigraphic unit heterotopic to DCS; instead, the Alpe di Specie member onlaps DCS slopes, and should therefore be included in the overlying HKS Formation.

It was only because of the focused attention associated with the geological mapping of the CARG project that the stratigraphic relationships of the Alpe di Specie member could be clarified.

Gianolla P. et al. (2018) - Note Illustrative della Carta Geologica d’Italia alla scala 1:50.000, F.016 Dobbiaco, 283 pp., SystemCart. Roma.

Neri C. et al. (2007) - Note Illustrative della Carta Geologica d’Italia alla scala 1:50.000, F.029 Cortina, 283 pp., SystemCart. Roma.

The Geological map sheet 539-Mogoro (Carg project in Sardinia)

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Keywords: Sardinia, Miocene basins, Pliocene volcanics.

The map sheet 539-Mogoro of the Geological Map of Italy in scale 1:50,000 has been carried out within the CARG Project (Law 160/2019), through an agreement between ISPRA - Geological Survey of Italy and the Autonomous Region of Sardinia- ARPAS (Geological Department), with the scientific support of the Department of Chemical and Geological Science of Cagliari University. The study area lacks a geological mapping from the old geological map project at 1:100.000 scale carried out about 90 years ago (Cavinato,1939), and just few small portions of the land were mapped with some detail before the CARG project. Its survey fills a knowledge gap in an area affected by significant urbanization and home to agro-pastoral activities relevant to the regional context.

There are three geological topics that predominantly characterize the 539-Mogoro Sheet. i) An Oligo-Miocene volcanic-sedimentary succession, subdivided in two tectono-sedimentary cycles (Assorgia et al., 1997; Carmignani et al., 2001): the first, Oligo-Miocene in age, characterised by a volcano-sedimentary succession related to the subduction of the Adria Plate below the European Plate, that infilled basins bounded by NW-striking normal/strike-slip faults; and a second cycle, characterised by unconformable silici-clastic rocks, late Burdigalian-Langhian in age, related to the east-directed slab-retreat related to the opening of the Algero-Provençal back-arc basin. ii) A Pliocene volcanic succession related to the opening of the Tyrrhenian basin. iii) The Campidano Graben, a small part of which outcrops in the sheet, related to the recent uplift (late Pliocene-Pleistocene?) of the Sardinian lithosphere (Cocco et al., 2024).

In addition to accurate mapping with a detail that holds up well even when reduced from the survey scale at 1:10,000 to the 1:50,0000 final representation scale, the most important advances in the geological knowledge of the area concern: i) the redefinition of the succession of the first Miocene cycle, where a more complex succession than previously known has been recognized and mapped, highlighting the role of tectonic evolution in influencing the depositional context and recognizing that these are shallow-water sediments, predominantly of a macro-tidal environment (Villanovaforru fm.) evolving to a lagoon- barrier system (Marmilla fm.); ii) the detailed mapping, sampling, and analyses carried out for Monte Arci have revealed a more articulated magmatic evolution than previously known, with the presence of explosive events, a more complex compositional variation, and the presence of a massive debris avalanche.

Assorgia A. et al. (1997) - A synthesis on the Cenozoic stratigraphic, tectonic and volcanic evolution in Sardinia (Italy). Boll. Soc. Geol. It., 116, 407-420.

Carmignani L. et al. (2001) - Geologia della Sardegna. Note illustrative della Carta Geologica della Sardegna alla scala 1:200.000. Mem. Descr. Carta Geologica d'Italia, 60, 283 pp., https://doi.org/10.13140/RG.2.1.1530.6723.

Cavinato A. (1939) - Nuovi risultati ed osservazioni nel rilievo geologico del foglio di Mandas 226. Rend. Acc. Naz. Lincei, 29(6).

Cocco F. et al. (2024) - Gravity field and geothermal structure of the Corsica-Sardinia Block. Terra Nova, 36(6), 1-10, https://doi.org/10.1111/ter.12738.

New palaeoenvironmental and structural data from the Mesozoic shallow-water carbonate platform of the Ernici Mts. (central Apennines, Italy): insight from the geological mapping of the sheet 390 – Frosinone

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Keywords: shallow-water carbonate platform, OAEs, Ernici Mts.

Field activity for the realisation of the geological sheet 390 - Frosinone allows us to observe under-investigated areas of the Ernici Mts (central Apennines, Italy). Here a Mesozoic shallow-water carbonate platform ranging from Late Triassic/Early Jurassic to Late Cretaceous is well exposed (Cosentino et al., 2010; Fabbi et al., 2023). This study highlights two different topics: 1) details on the stratigraphy of the Lower Cretaceous "*calcari ciclotemici a gasteropodi*" fm. (CCG - Berriasian *p.p.* - lower Aptian *p.p.*); 2) the structural setting of the Mesozoic shallow-water carbonates in the northern sector of the sheet. CCG mainly consists of whitish limestones with intercalations of light grey dolostones. Within this succession, a layer of black dolostone, about ten centimetres thick, has been observed, at the same stratigraphic position, in several outcrops of the dolomitic lithofacies (CCGa). In CCG, two stratigraphic sections were measured and sampled to characterise the microfacies and compositional variations observed between the light-coloured (whitish to light grey) and black layers of dolostones. Changes in chemical composition between the whitish and blackish dolostones (CCGa) were investigated in *situ* using the laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) facility at Roma Tre University. The results show a significant increase in the elemental concentration of redox-sensitive elements (As, Mo, V, Ni, S, Fe, U, Pb, Zn, Cu, Co). Additionally, SEM images, along with Energy-Dispersive X-ray Spectroscopy (EDS) and Wavelength-Dispersive X-ray Spectroscopy (WDS) analysis indicate the presence of siderite and pyrite aggregates. These features are generally associated with anoxic palaeoenvironments (Bodin et al., 2007; Meng et al. 2024). Biostratigraphic calibration performed on the collected samples has established a Hauterivian *p.p.* age for the investigated CCGa levels. A preliminary attempt for U-Pb dating of the CCGa black dolostone was carried out through LA-ICP-MS investigations. In the Tera-Wasserburg diagram, the U-Pb measurements on CCGa black dolostone yielded a lower intercept age of 122.9 ± 2.3 Ma (MSWD = 2.3; N = 46). These promising results suggest that the changes in the elemental concentration of the redox-sensitive proxies observed in the CCGa black dolostone were induced by the late Hauterivian Faraoni Oceanic Anoxic Event. Regarding the structural setting of the northern sector of the sheet, which is characterized by outcrops of "*calcari ciclotemici a gasteropodi*" (CCG - Berriasian *p.p.* - lower Aptian *p.p.*), "calcari e marne a *Salpingoporella dinarica*" (CMS - lower Aptian *p.p.*) and "calcari ciclotemici a requienie" (CIR - Aptian *p.p* - Albian), we noticed a different structural behaviour between the outcropping units. In the area, CIR is intensely folded and deformed, whereas the older units (CMS and CCG) appear not to be affected by plicative structures. This remark points to a detachment between folded and unfolded strata.

Bodin S. et al. (2007) - Enrichment of redox-sensitive trace metals (U, V, Mo, As) associated with the late Hauterivian Faraoni oceanic anoxic event. Int. J. Earth Sci., 96, 327-341, https://doi.org./10.1007/s00531-006-0091-9.

Cosentino D. et al. (2010) - Geology of the central Apennines: a regional review. J. Virtual Explorer, 36(11), 1-37.

Fabbi S. et al. (2023) - Stratigraphy and tectonic evolution of a portion of the Simbruini-Ernici Mountains (Central Apennines-Italy). Review and new data from detailed geological mapping. Geol. F. Trips Maps, 15(2.3), 1-40, https://doi.org/10.3301/GFT.2023.08.

Meng F. et al. (2024) - Siderite from the Tibetan Himalaya: Evidence for a low sulphate ocean during Oceanic Anoxic Event 1a (Early Aptian). Sedimentology, 71(7), 2358-2377, https://doi.org/10.1111/sed.13218.

Volcano-sedimentary evolution of an ancient oceanic crust: evidence from the Gimigliano metaophiolite (Southern Italy)

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Keywords: metaophiolites, Western Tethys, oceanic ridge.

This study explores volcano-sedimentary processes associated with an oceanic branch of the Western Tethys, currently preserved in the Gimigliano–Monte Reventino metaophiolite unit. This unit is exposed at the southeastern margin of the Sila Piccola Massif, within the northern segment of the Calabria–Peloritani terrane (southern Italy). Integrated field observations, conducted within the framework of the CARG Project (Geological and Thematic Mapping of Italy), combined with petrographic and mineralogical analyses of metabasites from the Gimigliano metaophiolite succession, have led to the identification of several lithofacies. The primary objective is to reconstruct the nature of their volcano-sedimentary protoliths and the processes responsible for their formation and emplacement. These lithofacies exhibit mineral assemblages dominated by epidote, chlorite, quartz, and albite, with minor muscovite and calcite, reflecting high-pressure/low-temperature (HP–LT) metamorphism, later overprinted by greenschist-facies conditions. The units are interpreted as metabasaltic flows derived from effusive submarine eruptions, as well as metahyaloclastites and metavolcaniclastites formed through explosive interactions between magma and seawater. This assemblage suggests that the Gimigliano area likely represented a sector of oceanic crust with elevated magmatic productivity, where magma–water interactions enhanced explosive activity and promoted dispersion of volcaniclastic material into the water column, accompanying the extrusion of basaltic lava. In contrast, other metaophiolitic complexes in the Calabria region, marked by the presence of pillow basalts, reflect lower effusion rates. The coexistence of these contrasting volcanic regimes, together with the widespread occurrence of metaultramafic rocks, portrays the Calabrian branch of the Tethys as a slow-spreading oceanic ridge. Variations in surficial volcanic expression were likely governed by localized differences in magma supply. This study demonstrates how a volcano-sedimentary approach to metaophiolite successions can yield significant geodynamic insights into the evolution of ancient oceanic ridges.

From data to apps: the evolution of CARG Project Database

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Keywords: CARG project, apps, geological data.

With the launch of the CARG Project – the Geological Map of Italy at a 1:50,000 scale – in the late 1980s, the Geological Survey of Italy produced 281 geological sheets, covering approximately 45% of the national territory. In addition, 25 subsurface sheets, 32 geothematic sheets at the 1:50,000 scale, and 12 marine geology sheets at the 1:250,000 scale have been created. All these products are currently published and available for consultation on ISPRA's institutional website.

Since 2020, a new phase of project funding has begun, leading to the activation of 112 new geological sheets and 19 geothematic sheets, each accompanied by its respective database.

Geological information derived from surface and subsurface surveys of both emerged and submerged areas of the Italian territory is organized within a complex geological database. This database is structured using a series of information layers and topological rules (Battaglini et al., 2009).

To enhance the traceability, accessibility, interoperability, and reusability of this vast amount of geological and geothematic data—in line with the FAIR principles and INSPIRE standards—a new platform has been developed within ISPRA's institutional website. This platform provides access to raster versions of geological sheets, explanatory notes, databases, and, where applicable, raster versions of subsurface sheets. The platform, known as CARG-GATE, allows users to browse an interactive map to track project progress, access information on activated sheets, and download sheets and explanatory notes indexed via Digital Object Identifier (DOI).

A significant development is the availability of downloadable geological databases, processed through a complex transcoding and validation workflow. Each geological sheet's database, indexed with a DOI and complete with metadata, is released in the open-source GeoPackage format. These databases are structured into seven thematic layers covering geology, geomorphology, and resources/prospecting. Each layer features conventional symbology designed according to the standards of the Geological Survey of Italy.

Furthermore, as part of the PNRR – GeoSciences IR Project, services and mobile applications have been developed to make this data accessible on mobile devices. Through the iOS and Android mobile app, users can view data related to geological units, tectonic elements, bedding, geomorphological features, and resource/prospecting areas. The app also supports geolocation and feedback submission on observed data.

The management and maintenance of these platforms are of paramount importance, as geological knowledge underpins all land-use planning and civil and environmental protection efforts. The accessibility of geological data is strategic for identifying natural resources such as groundwater, extractive, and mineral resources, and, most critically, for supporting geological hazard prevention and mitigation strategies.

Battaglini L. (2009) - Carta Geologica d'Italia - 1:50.000 - Progetto CARG: modifiche ed integrazioni ai Quaderni n. 2/1996 e n. 6/1997.Quaderni del Servizio Geologico d'Italia, serie III, 12(I), 166 pp.

New geological map of the Northern Apennine front – Po Plain transition zone (CARG 160 – Pavia sheet): surface-subsurface relationships and tectono-stratigraphic evolution

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Keywords: Northern Apennines front, CARG project, geological map.

The activities for the implementation of the CARG 160 – Pavia Sheet resulted in a brand new 1:10.000 scaled geological map of the hillslope sector, located between the towns of Casteggio and Stradella in the Oltrepo Pavese area (Northern Italy). Here, the transition between the outcropping sector of Northern Apennine Front and its foredeep basin, the Po Plain, takes place, within the framework of the central-western flank of the Emilian Arc structures. The study area, extensively exploited for vine cultivation, is characterized by the scattered distribution of outcrops and the pervasive development of weathering profiles and soils, making it very challenging to trace continuous limits between formations. Therefore, the approach used consisted in an accurate description of the few available outcrops, their sampling for petrographic and biostratigraphic analysis and the description of the alteration profiles associated with the lithotypes. Weathering profiles develops on the unaltered rock rarely exceeding 1 or 2 metres of thickness, so the recognition of the distinctive features of alterites associated with substrate units often allows to assess and trace the extent of formations despite their limited outcrop conditions. The sedimentary succession preserved in the area represents a typical active margin sequence. It includes an Upper Cretaceous to Miocene turbiditic succession, characterized by extensive arenaceous and marly deep-marine turbidites of the Val Luretta Formation which tectonically overlies younger units along a south-dipping, north-verging thrust fault with a general WNW–ESE orientation. The thrust is intersected by N–S-trending transfer faults, displacing the structure northward in the eastern part of the study area. North of the thrust fault, the Tortonian to Pliocene sedimentary succession extends across the area with a generally sub-planar attitude. Locally, this sequence is affected by gentle folding systems, with fold axes trending WNW–ESE. Moreover, the facies association indicates a shallowing-upward trend in the sedimentary environment, transitioning from deep to shallow marine conditions. This evolution led to the development of evaporitic sedimentation within restricted basins, followed by the reworking of these deposits by transitional deltaic and, later, continental fluvial systems associated with the Messinian Salinity Crisis. Eventually, shallow marine conditions were reestablished during the Pliocene. This work will be the baseline for future investigation of this sector of the Northern Apennine Front and for the understanding of the temporal and spatial relationship between its outcropping and buried portion. The integration of field and subsurface data will contribute to a more detailed reconstruction of the tectono-stratigraphic evolution of the area with particular focus on possible recent (Pleistocene) tectonic activity related with the debated seismogenic sources mapped close to the study area.

Shallow landforms and deep karst phenomena of the Marguareis Massif (North-West Italy). The experience of geological-geomorphological survey within the CARG Sheet no. 244 "Ormea"

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Keywords: geomorphological mapping, karst, Marguareis.

Preliminary data on shallow landforms and deep karst phenomena mapped during two years of activity within the four-year project for geological mapping of the new CARG Sheet 244 - Ormea 1:50.000 are presented. Sheet 244 is located on the western Alpine arc on the border between Liguria and Piemonte and includes the high mountain areas of the Marguareis Massif, the heart of the Marguareis Natural Park at the head of the Tanaro and Pesio Valleys. The Marguareis massif represents a high altitude karst and is one of the most extensive karst systems in Italy, featured by shallow landforms as large dolines, sinkholes, shallow holes, collapse canyons and karren fields and by an extensive systems of tunnels and deep holes. In fact, the study area is characterized by a vast absorbing area that extends from the ridge that includes Punta Marguareis, the highest elevation of the Ligurian Alps (2650 m), Pian Ballaur (2604 m) and Cima delle Saline (2555 m). It reaches westward the Colle dei Signori ridge, extending into French territory, and then develops southeastward to the Foce resurgence (1190 m) positioned in the Fascette Gorge in the upper Tanaro Valley with a karstification potential exceeding a thickness of 1400 m.

The predominant morphology of the entire drainage area is characterized by the presence of vast glaciokarst valleys, with evident landforms of extensive dissolution and collapse dolines. Only in areas where cretaceous lithotypes outcrop, characterized by arenaceous and shale limestones, abundant debris deposits are observed. Among the main caves of national significance that characterize the survey area the Piaggia Bella complex (43 km) with as many as 16 entries, the Labassa complex (21 km) and the Colle dei Signori complex (8 km) are present. In the Piaggia Bella area, deep karstification was strongly influenced by the geological-structural condition, characterized by the presence and geometry of an impermeable metamorphic basement (porphyroids and quartzites) that controlled groundwater circulation. The research activity involved geomorphological surveying with remote techniques and field surveys at the scale 1:10.000, cartographic restitution in a GIS environment through the integration of both newly collected data and previous data. The cartographic restitution in the GIS environment then involved the redefinition of the identified erosional landforms and deposits, adapting them to the base cartography (1:25.000/1:50.000) and modifying them according to the technical-scientific purposes of the Geological Sheet and the restitution format required by the ISPRA. The case study therefore aims to provide new insights for the up-to-date discussion on methodological approaches in geological-geomorphological mapping applications, such us field survey, use of pre-existing and newly defined databases, and final restitution in GIS environment.

New insights on the Late Pleistocene to Early Holocene evolution of the eastern Po Plain (Ferrara Area, Northern Italy)

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Keywords: late Quaternary, Po Plain, sin-sedimentary tectonics.

The combined use of sedimentological and geotechnical analyses, and the integration with geophysical investigations represent a powerful, multi-disciplinary approach to reconstruct the shallow subsurface stratigraphy of complex sedimentary successions, such as late Quaternary deposits of the Po Plain. In particular, the calibration of geotechnical parameters from CPTu tests (tip stress, sleeve friction, porewater pressure) with sedimentary facies observed on drill cores provides a detailed view of the subsoil, especially because of the large availability of geotechnical analyses in urbanized areas. Trends in geotechnical parameters from CPTu also provide crucial information to identify stratigraphic markers, such as peat layers or paleosols, that can be used for regional correlations.

More than 1200 continuous cores (including 16 newly performed drillings) were analysed and more than 1600 CPTu were interpreted for the realization of CARG Sheet 185-Ferrara, covering the eastern sector of the Po Plain. These data were integrated with stratigraphic information from 650 groundwater well-logs and about 350 boreholes, leading to the construction of five geological cross-sections (three approximately N-S oriented, two approximately W-E oriented). This allowed us to reconstruct the geometries of buried sedimentary bodies and the overall stratigraphic architecture. A key stratigraphic surface is represented by the Pleistocene-Holocene boundary, which is locally marked by paleosols in fine siliciclastics emphasizing a prolonged subaerial exposure. Paleosols correlate laterally with the sharp boundary between coarse-grained, fluvial sands and overlying fine-grained, organic-rich sediments that accumulated into marshes or poorly drained environments. The 3D model of this surface was reconstructed, making it possible to recognise a significant interference of the tectonic activity, even during the latest Pleistocene and the Holocene. On the other hand, the subsoil of the investigated area is characterized by well-known, still active structures (e.g., Ferrara Folds) belonging to the North Apennines accretionary wedge.

In the southern sector of the study area floodplain muds prevailed, crosscut by narrow, ribbon-shaped, Apennine-sourced sand channels, whereas in the central-northern sector laterally extensive, coarse-grained fluvial bodies persisted, related to an Alpine-derived sedimentary input. Unlike in the western areas of the Po Plain (sheet 184-Mirandola), the uppermost Pleistocene, W-E trending sandy channel-belt is split in two main branches, interposed by a muddy, inter-channel belt in correspondence of the Poggio Rusco and Casaglia anticlinal crests.

Multiscale Lineament Identification through Manual Extraction from Multiple Visualizations of DTMs: the eastern Lessini Mountains (CARG Project, Sheet 124, Verona Est, Italy)

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Keywords: Digital Terrain Model (DTM), remote sensing, lineaments.

Remote sensing and Digital Terrain Models (DTMs) analysis are now well-established tools for landform mapping, especially given the increasing availability of national and global datasets. Within the framework of the Italian CARG Project for producing the Geological Map of Italy at a 1:50000 scale, DTMs play a key role in improving geological interpretation by enhancing the understanding of surface structures and landscape evolution, supporting and improving field geological mapping.

However, lineament identification on remotely sensed data is often influenced by a high degree of subjectivity. As noted in previous studies, factors such as the operator's experience, observation scale, and DTM visualization method (e.g., artificial illumination azimuth) significantly affect the number, orientation, and length of extracted lineaments. Building on the methodologies of Scheiber et al. (2015) and Smith & Clark (2005), this study proposes a multiscale approach that employs multiple DTM visualizations to establish a reproducible workflow, aiming to minimize such subjectivity.

The study area is located in the eastern Lessini Mountains (Verona, Italy), characterized by Mesozoic and Cenozoic limestones in the west, Eocene volcanic rocks (mainly basalts) in the east, and Quaternary fluvioglacial deposits to the south. This area has undergone complex Alpine-related tectonic evolution, with the Castelvero Fault forming a major structural boundary between carbonate and volcanic units.

Lineaments were extracted from a 6-meter resolution DTM provided by the Veneto Region using GIS software at four scales (1:200,000, 1:100,000, 1:50,000, and 1:25,000) and through three visualization techniques (Ambient Occlusion, Hillshade with azimuth at 315°, and at 45°), resulting in twelve lineament maps. Rose diagram analysis of the lineament trends revealed two dominant orientations: NNW–SSE and WSW–ENE, with notable differences between volcanic and carbonate lithologies.

Comparison with existing geological maps (Servizio Geologico d'Italia, 1967) revealed significant discrepancies, suggesting that not all tectonic features are clearly reflected in the DTM data. This highlights the need for further fieldwork to verify the actual orientation and nature of geological structures.

In conclusion, the multiscale identification and analysis of lineaments using DTMs significantly enhance geological interpretation in the Lessini Mountains. The study underscores the differences with previous surveys and points to lithology-dependent variations in lineament orientation, emphasizing the value of this approach for guiding future geological investigations.

Scheiber T. et al. (2015) - Manual extraction of bedrock lineaments from high-resolution LiDAR data: methodological bias and human perception. GFF, 137(4), 362-372, https://doi.org/10.1080/11035897.2015.1085434.

Smith M.J. & Clark C.D. (2005) - Methods for the visualization of digital elevation models for landform mapping. Earth Surf. Process. Landforms, 30, 885-900, https://doi.org/10.1002/esp.1210.

Servizio Geologico d'Italia (1967) - Carta Geologica d'Italia, alla scala 1:100.000), Foglio Verona. ISPRA, Roma.

Stratigraphic reconstruction of the Eocene Mount Calvarina basaltic shield volcano using RRIM from high-resolution LiDAR data (CARG Project, Sheet 124, Verona Est, Italy)

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Keywords: red relief image maps (RRIM), Digital Terrain Models (DTMs), volcanic stratigraphy.

Over the past few decades due to their increasing availability and resolution and decreasing production costs, Digital Terrain Models (DTMs) have been extensively and fruitfully used in volcanology as a complementary tool to support geological mapping and conduct morphological and morphometric analyses. Among the visualization techniques developed for interpreting such data, the Red Relief Image Map RRIM) method - which is based on the integration of multiple topographic parameters (i.e., slope, positiv openness, and negative openness) - has proven particularly effective in highlighting subtle morphologic variations in volcanic terrains. The identification of volcanic landforms such as lava flows and eruptive vents through RRIM analysis, combined with field observations and geological data, supports geological mapping providing insights into the stratigraphic evolution of exposed volcanic sequences. Geological surveys are being carried out in the Lessini Mountains (Veneto, Italy) to create a new geological map (1:50,000 scale) within the CARG Project (Sheet 124, Verona Est). In the study area of the Mount Calvarina shield volcano, located between the Chiampo and Alpone valleys, the outcropping volcanic rocks are Eocene relatively homogeneous basaltic rocks currently classified as a single stratigraphic unit in the 1:100,000 map (Servizio Geologico d'Italia, 1967). This homogeneity, coupled with dense vegetation cover, poses challenges in reconstructing the stratigraphy using field observations alone. This study aims to subdivide the basaltic rocks of the Calvarina region into informal geological units with their own specific morphological features by means of RRIM. These units are stratigraphically classified after targeted Field ground truthing. Specifically, the basal portion of the succession comprises basaltic lava flows and hyaloclastites interbedded with calcareous layers, indicating a marine depositional environment. In contrast, the upper portion is composed of subaerial basaltic lava flows and volcanoclastic deposits, thus reflecting a trend of progressive emergence. In conclusion, this work provides a more detailed reconstruction of the Lessini Mountains volcanic evolution.

Servizio Geologico d'Italia (1967) - Carta Geologica d'Italia, alla scala 1: 100.000, Foglio Verona. ISPRA, Roma.

The tectono-depositional evolution of the foreland basin system of the Southern Apennines: a contribution from a revised litho-biostratigraphic and structural framework of the Miocene Castelvetere Formation cropping out at the NE Basilicata-Campania border (CARG Project sheet Muro Lucano n. 469)

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Keywords: Miocene Castelvetere Formation, tectono-depositional Southern Apennines evolution.

The Castelvetere Formation (CVT) is a deep-marine succession of the Southern Apennines, nowadays usually considered as deposited in a wedge-top-type basin during upper Tortonian-lower Messinian times (e.g. Servizio Geologico d'Italia, 2002 and reference therein; Vitale et al., 2020; Ferranti et al., 2024). The geological mapping of the sheet Muro Lucano n.469 at a 1:50000 scale of the CARG Project has provided the opportunity to revise the bio-lithostratigraphy and analyse the tectonic structures in well exposed successions located in a key area of the NW Basilicata-Campania border zone (Castelgrande, Laviano and Muro Lucano villages).

Results of the investigation of the CVT in the aforementioned area are listed below.

CVT lies on non-orogenic deposits, such as the Apennine Carbonate Platform succession, along a surface of angular unconformity marked by a basal conglomerate or Numidian hard yellowish quartz-rich arenites; and is covered unconformably by Pliocene sediments of the Ariano Supersynthem.

It consists of up-to-tens-of-metres-thick packages of amalgamated medium-to-coarse-grained sandstones with mostly-matrix-supported conglomerates with erosional bases, that can be flanked and vertically covered by up-to-tens-of-metres thick muddy packages. In addition, exotic masses, comprising varicoloured chaotic muds of the Argille Variegate Group and Apennine Carbonate Platform boulders, are present at different stratigraphic levels.

Age of CVT is Burdigalian-lowermost Serravallian as indicated by nannoplankton analyses of tens of pelitic samples collected from numerous sections spanning from base to top of its stratigraphic interval.

It is highly affected by tectonic deformation outlined by: (1) large-scale folds with hinge lines oriented E-W and ENE-WSW, respectively; (2) overturned S-to-SSW-dipping sandstone beds, (3) SSW-dipping high-angle reverse/transpressive faults superposing the Apennine Platform on CVT, and (4) Plio-Quaternary extensional E-to-ESE-oriented high-angle faults.

The above study allows to reconstruct the following step-by-step evolution of the CVT in the study area: (i) structuring of a foredeep depozone, floored by Apennine Platform and Numidian deposits, no later than the Burdigalian; (ii) infilling of the foredeep with CVT sediments during tectonic over-steepening of the foredeep inner slope, at least up-to the lowermost Serravallian; (iii) incorporation of the CVT sediments and the underlying units in a wedge-top depozone, during a contractional stage occurring no later than the Pliocene; and eventually (iv) post-orogenic deformation.

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Servizio Geologico d'Italia (2002) - Carta Geologica d'Italia alla scala 1:50.0000, Catalogo delle Formazioni, Fascicolo III - Unità validate.

Vitale S. et al. (2020) - Structural and Stratigraphic Setting of Campagna and Giffoni Tectonic Windows: New Insights on the Orogenic Evolution of the Southern Apennines (Italy). Geosciences, 10(10), 405, 1-23, https://doi.org/10.3390/geosciences10100405.

The frontal sector of the southern Apennines between Acerenza and Oppido Lucano (Basilicata, southern Italy): sedimentologic, stratigraphic and structural features

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Keywords: Southern Apennines, mixed carbonate-siliciclastic systems, tectonics and sedimentation.

Between Acerenza and Oppido Lucano localities (Basilicata, southern Italy), the outcropping front of the Apennines is mainly characterized by two Cretaceous to Tortonian tectonic units (respectively the San Chirico tectonic Unit, above, and the Daunia tectonic Unit, below) unconformably overlain by Plio-Pleistocene wedge-top deposits (Labriola et al., 2008; Chiarella et al., 2019). The mixed Lower-Pleistocene siliciclastic-carbonate shallow-marine deposits outcropping in this small frontal sector of the Southern Apennines locally represent the last sedimentologic evidence of the complex development of this still active mountain chain. A detailed geological survey allowed us to recognize the main sedimentologic features of these mixed deposits and the stratigraphic and structural framework in which they developed.

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Labriola M. et al. (2008) - Caratteri stratigrafico-strutturali della porzione frontale dell'Appennino lucano compresa fra Acerenza e Oppido Lucano (Potenza, Basilicata). Memorie Descrittive Della Carta Geologica D'Italia, 77, 111-118.

Quaternary tectonic and landscape evolution of the north-western sector of the Maiella ridge (Central Apennines, Italy)

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Keywords: landscape evolution, drainage changes, Mt. Maiella.

The revival of Italy's National Geological Mapping Project (CARG Project) has created a valuable opportunity to combine existing knowledge with new, detailed field studies. By taking an interdisciplinary approach - bringing together structural geology, stratigraphy, sedimentology, remote sensing, and advanced dating techniques - we can better understand how tectonic forces, erosion, and sedimentation shaped the landscape over time.

This methodology was applied to the Guardiagrele area (Sheet n. 370 of Italy's Geological Map), revealing new details about the Quaternary evolution of the Maiella ridge (a large east-verging anticline) and how its drainage networks developed during the Quaternary.

During the Pleistocene morphogenesis the Maiella area was dominated by polyphasic continental erosional processes, leading to the formation of extensive debris covers and mostly coarse alluvial deposits, passing to transitional environment deposits. On the western flank of the Maiella ridge, the Orta River basin shows evidence of a relict hydrographic network, which featured a main N-S trending watercourse (paleo-Orta), roughly parallel to the developing ridge. Following a phase of intense erosional activity linked to significant uplift, the NW-SE branches of the network set on the backlimb of the Maiella anticline (Vallone di San Bartolomeo-Santo Spirito and Valle dell'Orfento) deepened and extended their course disrupting the former N-S trending streams, whose remnants are preserved in some relict valleys. Among these, Valle Giumentina hosts an archaeologically significant site of global importance, which has attracted scholarly interest since the early 20th century (Demangeot & Radmilli, 1953; 1966). Multidisciplinary studies documenting human occupation at Valle Giumentina (Villa et al., 2016) have analyzed its sedimentary infill - partly lacustrine-palustrine - reconstructing in exceptional detail a stratigraphic record spanning ~150 ka within paleoenvironmental and paleoclimatic contexts from MIS15 to MIS12.

These studies provide a robust chronological framework for reconstructing the Quaternary geological evolution of the Maiella area. Combined with interdisciplinary data collected for Sheet n. 370 Guardiagrele, they allowed us to outline the stratigraphic and tectonic context of sedimentary events, including the massive slope failures materialized by the rock avalanches deposits of the Orta valley (e.g. the Caramanico Terme and Sant'Eufemia a Maiella breccias). This approach also contributed to define the timing of tectonic events and the spatiotemporal relationships between the oldest continental successions along the ridge margins, the alluvial deposits cropping out downstream in the Pescara valley (Sheet n. 360 and 361 of Italy's Geological Map*;* Urbano et al., 2017) and the marine formations further to the north (e.g. the Turrivalignani fan delta conglomerates).

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Geological mapping and hydrostratigraphy of the regressive Quaternary deposits of the Bradanic Trough cycle: the key-area between Banzi and Genzano di Lucania towns (Basilicata, southern Italy)

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Keywords: Basilicata, Bradanic Trough, hydrostratigraphy.

A detailed geological survey has been performed between Banzi and Genzano di Lucania towns, in the Basilicata Region (southern Italy). The studied area is located in the central part of the Bradanic Trough (the Plio-Pleistocene south-Apenninic foredeep), where well exposed Quaternary deposits represent the outcropping part of the in-fill succession of the basin. The outcropping lower Pleistocene deposits form a regressive succession made up of silty clays (Argille subappennine formation) followed by a sandy-conglomeratic lithostratigraphic unit, up to 100 m thick and continental to marine in origin. This unit is made up mainly of conglomerates in the WNW sector (near Banzi) and mainly of sands in the E-SE sector. Conglomerates, here identified as a member (Conglomerato di Banzi) inside the Monte San Marco Formation, interfinger with sands through four mappable tongues. A thick mappable conglomeratic lens was also found inside the mainly sandy part of the Monte San Marco Formation. The stacking pattern of these bodies and their interfingering with sands and clay layers, allowed the overlying of at least 3 suspended groundwaters (and related springs/ fountains) whose intriguing hydrostratigraphy can be appreciated only through detailed geological mapping and geological sections.

Beyond the hammer and compass: technologies and new perspectives from the realization of the Geological Sheet 313 "Camerino" (CARG Project)

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Keywords: CARG Project, geological mapping, Sheet 313 Camerino.

Geological mapping remains a key source of new stratigraphic, structural, geomorphological, and cartographic data, even in well-studied areas with excellent exposures of sedimentary successions and associated structural features. A notable example is the Sheet 313 "Camerino" of the Geological Map of Italy at 1:50,000 scale, which covers approximately 600 km2 between the Umbria-Marche Apennines and the Periadriatic hills. This area hosts the type-locality of the Jurassic–Miocene Umbria-Marche Succession, exposed in the hanging wall of major Late Miocene thrusts (Mt. Primo–Mt. Igno and Sibillini Mts.), which shape the Umbria-Marche and Sibillini ridges. Meso-Cenozoic carbonate units are overlain by two different siliciclastic successions: the *Camerino formation* (Tortonian *p.p.*-lower Messinian) in the inner sector, and the *Laga formation* (Messinian *p.p.*) in the eastern one. The Periadriatic foothills also host the syn- and post-Messinian Salinity Crisis (MSC) deposits. Quaternary continental deposits unconformably overlie the deformed bedrock and were classified using the UBSUs adopted in the already published CARG Project geological maps of the Marche region.

Traditional field mapping was integrated with GIS-based digital mapping tools, enabling the collection of accurate, organised and georeferenced information aligned with the CARG Project Database and the project Guidelines (Vita et al., 2022). In addition, UAV-derived virtual outcrop models further aided the study of otherwise inaccessible exposures.

Detailed field mapping reveals a complex tectono-stratigraphic evolution driven by multiphase extensional tectonics during pre-orogenic stages. Despite limited Jurassic outcrops, the complex paleotectonic-paleogeographic setting made of pelagic carbonate platforms and intervening basins inherited from the Tethyan rifting has been reconstructed. Locally, Early Jurassic normal faults show evidence of Bajocian reactivation, marked by syn-tectonic breccias, neptunian dykes and faults sealed by Middle-Upper Jurassic pelagites. Cretaceous tectonic perturbations led to breccias deposition within the *Maiolica* (Mt. Primo breccias) and controlled the dispersal of calciturbidites in the *Scaglia Rossa*. Late Miocene forebulging-related normal faults formed hanging wall basins filled with thick siliciclastic successions, while uplifted footwalls experienced stratigraphic condensation and discontinuities (e.g., MSC deposits resting directly on the Tortonian *Schlier*).

The stratigraphic relationships between pre-, syn- and late-orogenic deposits helped constrain the time interval of activity of the main thrusts.

Ongoing integration of field and subsurface (seismic and borehole) data will lead to the realization of a 3D geological model for the study area.

Vita L. et al. (2022) - Aggiornamento e integrazioni delle linee guida per la realizzazione della Carta Geologica d'Italia alla scala 1:50.000 Progetto CARG. Modifiche ed integrazioni ai quaderni n. 1/1992, n. 2/1996, n. 6/1997 e n. 12/2009. Quaderni del Servizio Geologico d'Italia, serie III, 15, 261 pp., https://progetto-carg.isprambiente.it/quaderno15&oggettidigitali/Quaderno_N_15.pdf.

Paleotectonics and stratigraphic architecture of the Tortonian-Messinian Camerino and Laga siliciclastic basins: a different perspective

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Keywords: siliciclastics, foreland basin, field mapping.

New insights into the paleotopography, stratigraphy, and tectonic events around the Tortonian-Messinian time interval in the Central Apennines were made possible by geological field mapping of the Sheet 313 "Camerino" at 1:50,000 of the CARG Project.

While interpretations vary, Late Miocene turbidite basins are typically regarded as wedge-top depozones of the Apennine thrust belt. New field data suggest that, during the early Tortonian to basal Messinian, the Sibillini Mts. area acted as a structural high, bounded by normal faults aligned to the Apennine axis. These faults formed a staircase of blocks descending toward the Camerino Basin (west) and toward the Laga Basin (east). Intra-basin highs (e.g., Belforte–Villa Rofanello, a southern extension of the Miocene Cingoli high), segmented by WSW–ENE faults, increased structural complexity. The hanging-wall basins hosted thick, resediment-rich successions: calciclastics (*marne con cerrogna-Schlier* formations) and siliciclastics (Camerino/Laga formations), with northward pinch-out geometries. On horst blocks, condensed pelitic deposits or Messinian gypsarenites overlying the Schlier suggest starved conditions.. The proximity of thick turbidites to structural highs implies steep submarine fault scarps onlapped by basin fill. Basin margin successions show meso-scale normal faults following the scarps trend, now rotated by subsequent orogenic deformations. Megabreccias sourced from the steep escarpments, as well as the thickness variations of the pre-tectonics units underlying the siliciclastics, and their unconformable relationships were interpreted as evidence of backstepping of fault-scarps. Mapping breccias bodies was pivotal for identifying the basin margins and reconstructing the asymmetric (i.e., half-graben) basin geometry, with depocentres located adjacent to the fault scarps. Locally, neptunian dykes filled with arenaceous deposits occur.

Major faults such as Mt. Valvasseto–Mt. Letegge and Piobbico–Monastero, with significant stratigraphic offset and no evidence of post-orogenic reactivation, are attributed to this Miocene extensional phase.

This complex stratigraphic architecture reflects a tectonically driven forebulging of the foreland basin preceding orogenic compression. No syn-compressional deposits were identified in the Camerino basin, but progressive onlaps of the upper part of the *membro del Lago di Campotosto* (Laga formation, pre-Messinian Salinity Crisis – MSC), *formazione di Sapigno* (syn-MSC), and *Formazione di San Donato* (post-MSC) onto the Sibillini Mts. anticline record growth geometries linked to the late activity of the Sibillini Mts thrust during the Messinian, which was eventually sealed by the post-evaporitic, pre-Pliocene *Formazione a Colombacci*.

Validation process and critical review of a 3D subsurface model: a test on the Trento Platform (Southern Alps, NE Italy)

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Keywords: 3D models, validation, Trento Platform.

3D geological modelling aids prediction of subsurface geology and finds application both in industry and academic research. Although a range of different approaches (*e.g.*, implicit vs. explicit) exists, geological modelling entails interpolating (often sparse) outcrop and borehole observations regarding lithological composition and geometry of a geological structure and quantifying residual uncertainty. Although most often appealing, a 3D geological model must be in first place robust, and its robustness validated against observations. It is widely recognized that robust 3D geological models are valuable tools for tackling uncertainty in a range of industry projects, from ore mining to tunnelling and nuclear waste management, and can help promoting geological knowledge in the general public. In Italy, the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) encourages the production of 3D geological models as part of the national 1:50.000 scale geological mapping project (CARG).

Newly acquired geological mapping data from an area of ca. 42 km^2 belonging to the 1:50.000 scale geological map sheet 081 "Rovereto" (Monte Pasubio, Trento Platform, NE Italy) were used to test an iterative explicit modelling workflow, which include multiple stages of validation. 3D modelling was accomplished using Move (PE Ltd) and the following workflow: 1) high-detail 1:10.000 geological field and remote sensing mapping; 2) digitalization of the geological map in a GIS system using a cm-resolution LiDAR DEM; 3) construction of a geological cross-sections grid; 4) 3D kriging interpolation of the obtained 2D horizons and faults to reconstruct the 3D distribution of each geological unit recognized in the area.

According to the field mapping, the Jurassic geological units cropping out in the study area exhibit flat geometries with a regional N-NW strike attitude, display constant thickness and are affected by the NW-SE trending sinistral strike-slip faults of the Schio-Vicenza system.

The resulting 3D model was critically evaluated and iteratively improved using the following validation process: a) check of the surfaces interpolation with the topography (should corresponds with the mapped geological limits); b) creation of thickness maps (should be coherent with field observations); c) edit of the geological cross sections if needed; d) restart the modelling from step 4 (kriging interpolation).

This study demonstrates how validation by a detailed geological interpretation lead to the production of new and more reliable 3D models with an integrative and iterative process, especially needed when data are collected with an irregularly scattered distribution.

The Variscan basement of the geological sheet 546-Guspini (SW Sardinia)

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Keywords: Variscan basement, Sardic phase, back-thrusts.

The geological sheet 546-Guspini covers an area of the SW Sardinia Variscan basement, where sectors of the External and Nappe zones of the chain crop out.

The preliminary results of the field mapping activity shed new light on the structural style of this portion of the Variscan basement, showing some differences compared to the existing geological maps. The main structure outcropping in the area of the sheet 546-Guspini is the Arburese thrust, a first order shear zone separating the Variscan External Zone from the Nappe Zone, here represented by the Arburese Tectonic Unit, that overthrusted with a top-to-the-west transport direction the External Zone. The stratigraphic succession of the External Zone is well defined and spans in age from lower Cambrian to Devonian, with a Middle Ordovician stratigraphic gap, marked by the Sardic Unconformity, related to the Sardic Phase. The stratigraphic succession of the Arburese Unit is less defined and mainly consists of a Cambrian-Ordovician monotonous siliciclastic sequence with interlayered volcanic rocks.

The main findings can be summarized in four main points:

1. In the western sector of the sheet, the Cambrian-Ordovician stratigraphic succession of the External Zone is affected by back-thrusts, never mapped before. These structures are the continuation of the back-thrusts outcropping to the south of sheet. The recognition of these back-thrusts allows to unravel the complex geometric relationships between the pre- and post-Sardic formations. As an example, the lower Cambrian limestones, that host sulphide mineralisation and are embedded within the Upper Ordovician succession, previously interpreted as blocks bounded by high angle normal faults, are rather tectonic slices bounded by east-directed thrusts.
2. The Upper Ordovician succession of the External Zone in the footwall of the Arburese thrust is affected by a E-W subvertical pervasive cleavage and by closed to isoclinal folds with fold axes trending E-W. Southward, the attitude of the cleavage and the trend of the folds change to N-S. The different orientation of cleavage and folds suggests a change in the shortening and transport direction possibly related to the emplacement of the Arburese Tectonic Unit on the External Zone.
3. Between the Arburese Tectonic Unit and the External Zone a volcano-sedimentary succession has been mapped. Because similar stratigraphic successions have not been recognized neither in the External Zone nor in the Nappe Zone, this unit is difficult to ascribe to the known stratigraphic successions of the Variscan tectonic units. The age of the volcanic rocks is for now unknown, but their dating is ongoing.
4. Three systems of post-Variscan faults, in previous maps underestimated, affect intensively the stratigraphic succession of the External Zone. The most important are oriented NW-SE and bear huge F-Ba (Pb-Zn) mineralization. The cross-cut relationships with the other fault systems, NNE-SSW and E-W oriented, are not well defined yet, as well as the age of deformation.

Sheet 158 "Casale Monferrato" of the Geological Map of Italy at 1:50.000 scale (CARG Project): preliminary results on the relationship between tectonics and sedimentation

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Keywords: CARG, geological mapping, sedimentary geology.

We present an update of the geological mapping of Sheet 158, *"Casale Monferrato"*, of the Geological Map of Italy (CARG Project), one and a half years after the start of the project in winter 2024. The sheet is located at the northwestern termination of the Northern Apennines and is characterized by an upper Eocene–Miocene Epiligurian succession resting unconformably on the External Ligurian Units, remnants of the Alpine accretionary wedge. The sedimentary succession has been subdivided into four Unconformity-Bounded Stratigraphic Units (UBSUs), separated by regionally extensive erosional surfaces identified through field criteria. The first UBSU includes the hemipelagic marls of the Monte Piano Formation (upper Eocene), locally interbedded with bioclastic turbidites. The second UBSU, comprising the Cardona and Antognola Formations (Rupelian–Aquitanian), is intensely deformed by WNW-striking transpressive faults and overlain by a prominent angular unconformity. The third UBSU (Burdigalian–Serravallian) consists of the Pietra da Cantoni Formation, representing a transgressive carbonate ramp system evolving into deeper marine settings. Another angular unconformity marks the base of the fourth UBSU, consisting of Tortonian–lower Messinian hemipelagic sediments (Sant'Agata Fossili Marls), overlain by evaporitic deposits of the Vena del Gesso Formation, which record the Messinian salinity crisis. Post-crisis sedimentation is represented by Zanclean marine marls (Argille Azzurre Formation) grading upwards into inner shelf sandstones (Sabbie di Asti Formation).

The crosscutting relationships between faults and unconformity surfaces define a complex tectono-stratigraphic framework resulting from six main tectonic phases: (1) late Cretaceous–early Eocene, (2) late Eocene–Oligocene, (3) Chattian–early Miocene, (4) late Serravallian, (5) late Messinian, and (6) early Pliocene. Additional fieldwork and seismic line analysis will enable a more refined understanding of the stratigraphic, sedimentological, and structural framework, providing better constraints on the tectono-sedimentary evolution of this sector of the northwestern Apennines.

The contribution of the CARG Project 286 Poggibonsi to the geology of the Central Tuscany: the setting of the Ligurian Units of the Chianti Mountains

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Keywords: CARG, Ligurian Units, Central Tuscany.

This abstract presents the results of the CARG Project 286 Poggibonsi 1:50.000 scale (Cornamusini et al., 2025), which was carried out with the aim of contributing to the geology of Central Tuscany as well as of the Northern Apennines. The CARG 286 project comes after the detailed Cartographic Project of the Region of Tuscany at a scale of 1:10.000, while important geological maps from the literature showing the Ligurian Units are those of Bortolotti (1962) and Merla & Bortolotti (1967). The new CARG map introduces important updates and innovations compared to previous maps, both in terms of geological mapping and interpretation of the data, which are of great importance for the development of a modern evolutionary framework. The Ligurian Units mainly characterise the eastern sector of the map and are organised in a stack of tectonic units formed during the orogenic phase, with the Morello Unit below and the Monteverdi M.mo Ophiolitic Unit at the top, representing the upper remnants of the Apennine accretionary prism. The Morello Unit extensively outcrops in the eastern portion of Sheet 286 (Chianti Mountains Ridge) and presents a deformed stratigraphic succession affected by tectonic folds, slices and thrusts. The lower stratigraphic terms form a composite succession from the Cretaceous to the early Eocene, with highly deformed shales, limestones (Sillano fm.) and turbiditic sandstones (Pietaforte Fm.), with a chaotic ophiolitic complex in the lower part. The uppermost stratigraphic term is represented by the calciturbiditic system of the Monte Morello fm., early-?middle Eocene in age. The above Monteverdi M.mo Ophiolitic tectonic Unit is formed only by a limestone helminthoid flysch, Late Cretaceous in age. Below the Ligurian Units, through an important tectonic boundary, are discontinuous tectonic slices referable to the Canetolo Unit and below, the top of the Falda Toscana, as evidenced by tectonic windows aligned along large-scale NNW-SSE anticlines. The Canetolo slices are composed of Upper Cretaceous to upper Eocene shales, marly limestones and turbidite siliciclastic sandstones with rare volcano-arenites, with a strongly deformed setting typical of the tectonic mélanges, reminescent of the Sestola-Vidiciatico shear zone of Remitti et al. (2012). The upper part of the Tuscan Nappe consists of of turbidite siliciclastic sandstones, marlstones and chaotic shaly olistostromes of latest Chattian to earliest Aquitanian age. Differently, the Ligurian Units of the western part of the Sheet 286 (Middle Tuscan Ridge) are represented by ophiolitic units dominated by the highly chaotic Argille a palombini fm., which directly overlies through a low-angle normal fault, the Calcare Cavernoso Fm., a megacataclasite formed during deformation phases with dolomitic and evaporitic 'primary rocks' of the Late Triassic, which marks the base of the Tuscan Nappe.

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Remitti F. et al. (2012) - Deformation, fluid flow, and mass transfer in the forearc of convergent margins: A two-day field trip in an ancient and exhumed erosive convergent margin in the Northern Apennines. In: Vannucchi P. & Fisher D. (eds.), Deformation, Fluid Flow, and Mass Transfer in the Forearc of Convergent Margins: Field Guides to the Northern Apennines in Emilia and in the Apuan Alps (Italy). Geological Society of America Field Guide, 28, 1-34, https://doi.org/10.1130/2012.0028(01).

Geological and structural analysis of the Duino cliffs and Sistiana bay (Gulf of Trieste, Italy) through field surveys and 3D outcrop modeling

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Keywords: foredeep evolution, virtual outcrop models, Carso/Kras.

The Duino cliffs and the bay of Sistiana are iconic coastal areas in the Gulf of Trieste (Italy). There, vertical to overturned Upper Cretaceous to Paleogene carbonate strata of the Dinaride-related Carso fold forelimb dive into the Adriatic Sea. Despite the apparent overall simplicity, the detailed structural framework is still unclear, especially the tectonostratigraphic relationships between outcropping geological units and a pivot regional disjunctive fault passing through the Sistiana Bay (e.g., the "Sistiana Fault", "Sistiana Line", or "Sistiana Bending Zone") has only been hypothesized or inferred rather than constrained by field evidence.

This work aimed to clarify key aspects of the area's structural evolution through an integrated field and close-range remote sensing-based approach. The work also benefitted from recent observations conducted for the CARG project in the adjacent Sheet 110 "Trieste" of the Geological Map of Italy at 1:50000 scale, providing new insights into the stratigraphical relationships of the outcropping units. Thin-section analysis was used to characterize facies, biostratigraphy, and diagenetic and structural features. A detailed fracture analysis – including orientation, type, dimension, and topology – also assisted by 3D outcrop models realized through Structure-from-Motion Multi-View Stereo (SfM-MVS) photogrammetry, shed new light on the deformation mechanisms that led to the present-day geological configuration of the area.

Field investigations did not reveal a distinct fault plane consistent with the structural framework proposed by previous authors. Results, however, point to marked longitudinal variability characterized by stratigraphic hiatuses and lateral heterogeneity in both thickness and facies characteristics. These observations suggest the presence of high-angle transversal st ructural elements that acted prior to the formation of the Carso anticline. These extensional features were probably related to transversal structures of major longitudinal normal faults developed in connection with the peripheral bulge and the subsequent foredeep stage in the framework of the Dinaric fold and thrust belt during Late Cretaceous. The same transversal structures, inherited and partially reactivated in subsequent phases, were likely responsible for the origin of the Sistiana fault myth, which lacks clear field evidence such as an evident fault plane with coherent kinematic indicators.

From mountain belts to basins: enhancing the role of 3D geological models

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Keywords: 3D geological modeling, geological mapping, CARG.

Three-dimensional geological modeling techniques have become fundamental tools for integrating and reconciling diverse geological and geophysical data. Over recent decades, the development of advanced — including open-source — software and methodologies has broadened the community of geologists incorporating 3D modeling into their workflows. These models are now essential for achieving a comprehensive understanding of geological architecture and evolution of an area, and for quantitatively testing conceptual models traditionally constrained by surface data.

In Italy, 3D geological models have been built for extensive regions both in fold-and-thrust belts (e.g., RETRACE-3D, 2016–2018 Central Italy seismic sequence) and in foreland basins (e.g., GeoMol, HotLime EU projects), using vast geological and geophysical datasets. Interpreted by multidisciplinary teams, these models highlight the strategic role of 3D modeling as a comprehensive and shared framework. They support a better understanding of the interplay between sedimentary and tectonic processes over time (Amadori et al., 2019), help detect elusive structures in subsiding basins (Maesano & D'Ambrogi, 2016), and enable fault activity quantification (e.g., timing, slip rates, deformation partitioning) (Buttinelli et al., 2021; Maesano et al., 2024) through robust restoration workflows.

Building on these experiences, 3D geological models are now extensively developed within the CARG project as integrated products alongside 2D geological and subsurface geology sheets.

They offer detailed insights into the subsurface of areas of about 570 sqkm, significantly enriching geological knowledge. Geologists involved in both mapping and 3D modeling benefit from multidisciplinary teamwork — including stratigraphy, structural geology, and geophysics — to interpret surface and subsurface data, the latter mainly provided by ENI.

To date, in the CARG project seven 3D models have been completed and fifty more are expected within five years. These 3D models provide a solid base to better constrain hypotheses on tectono-sedimentary evolution across different geological contexts. They also enable the quantitative definition of processes and volumes, offering input for applications with significant societal impact (e.g., seismic hazard assessment, urban geology, resource management, and remediation of contaminated sites).

To facilitate access to the CARG 3D geological models, the Servizio Geologico d'Italia has launched Geo-IT3D (https://geo-it3d.isprambiente.it), a web viewer that enables interactive exploration of the models, with tools for user-defined cross-sections, maps, and virtual boreholes, all exportable as reports. As with all CARG products, and in line with the procedures set in the GeoSciences IR project, 3D models are described using standard metadata and made publicly available under a CC-BY open license via OGC-compliant download services.

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Gran San Bernardo and Monte Bianco geological maps, CARG project, Aosta Valley

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Keywords: CARG project, Aosta Valley geology, Western Alps.

The Gran San Bernardo (069) and Monte Bianco (068) geological maps of the 1:50.000 Geological Map of Italy (CARG project) cover the left side of the Aosta valley, between its central part and its head, and extend for about a third to the Swiss sector (Canton Valais) and, to a lesser extent, in France (Chamonix). The field and laboratory work of both maps is completed, their printing is in progress, and we would like to anticipate the main news on the structural, metamorphic and stratigraphic setting of this key sector of the NW-Alps. As shown in the "regional tectonic scheme", this sector of the collisional belt consists, from top to bottom, of four Europe-vergent tectonic domains (Servizio Geologico, 2015; Ballèvre et al., 2018; Passeri & Dal Piaz, 2023; Arienti et al., 2024): i) the Austroalpine nappe system, derived from the Adriatic continental margin and related extensional allochtons, including the lower crust of the Valpelline top unit, the underlying Permian granitoid and gabbroic layers of the Arolla Series, and the Roisan-Dolin cover units; ii) the upper ophiolitic Combin unit of the sutured Mesozoic Piedmont ocean, also including exotic cover units of continental affinity (whereas the eclogitic Zermatt-Saas unit is not present in these maps); iii) the middle-Penninic Gran San Bernardo system - a stack of basement and cover nappes derived from the Briançonnais microcontinent (or prepiemontese zone), and the external-Penninic Sion-Courmayeur or Valais zone, which brings together the thin-skinned units of the Piccolo San Bernardo, the Versoyen ophiolites, the Tarentaise trilogy, the Pyramides calcaires and the Penninic frontal melange; iv) the Helvetic zone, derived from the transpressive inversion of the European passive margin, including a pre-granitic complex, the Mont Blanc granite, adherent cover units, and the Helvetic decollement cover nappes.

More in detail, the Gran San Bernardo system encompasses, from top to bottom, the Monfort nappe (Métailler and Fallère Variscan and/or older units), the Siviez-Mischabel and Ruitor-Pontis polymetamorfic basement and the Briançonnais cover units, followed by the arenitic-psephitic and coal-rich beds of the Permian-Late Carboniferous Houillère zone, the Costa Serena black slates and marbles, and the tectonic (Rodzo) and deformed sedimentary (Pierre Avoi) melanges along the Briançonnais frontal thrust.

The Austroalpine-Penninic system is a relict oceanic and continental subduction zone with eclogitic to blueschist facies signature of Late Cretaceous-Eoceene age, later reworked by the collisional thermal relaxation and greenschist facies overprint. From the Oligocene, the orogenic front expanded into the European margin, and the nappe stack was frontally accreted by the Helvetic crustal slices. Geological and structural data of the polyphase deformations acquired in these and nearby maps of the Aosta valley are synthesized by crustal and lithospheric cross-sections and a 3D structural model.

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Mineral deposits of the CARG 546 "Guspini" area and workflow for the first metallogenic thematic sheet of Italy

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Keywords: ore deposits, CRM, raw materials, metals.

The sheet n. 546 "Guspini" of the Italian Geological Mapping Project (CARG Project) was chosen by ISPRA for the development of a prototypal metallogenic thematic map whose workflow would be potentially appliable in other regions of Italy. The geology of the "Guspini" sheet is dominated by Paleozoic rocks, represented by a) Cambrian-Middle Ordovician low-grade siliciclastic and volcanic units of the *Arburese Tectonic Unit* – Nappe Zone of the Variscan basement – which overthrusts b) the lower Cambrian-Lower Devonian very low-grade siliciclastic and carbonate successions of the *External Zone* of Iglesiente. The two domains are both polydeformed by pre- and Variscan tectonics with different tectonic styles: isoclinal folding in the Arburese Unit, upright folds framed in a regional "dome and basins" structure in the External zone. The basement is intruded by late-Variscan post-collisional granitoids, namely the Arbus (304±1 Ma) and Linas pluton (289±1 Ma). This geological complexity corresponds to a remarkable metallogenic variety. The "Guspini" sheet covers some of the main historical mining districts of Italy with several ore deposits of prime economic relevancehosted in the Paleozoic rocks (e.g., Montevecchio, Buggerru, Arenas Zn-Pb mines). Three main groups of deposit types with specific metal assemblages can be distinguished (Deidda et al., 2020; Scano, 2022; Naitza et al., 2024, and references therein): 1) pre-Variscan (Zn-Pb(-Fe) Mississippi Valley-Type (MVT) deposits); 2) late-Variscan (Zn-Pb-Fe-Cu, W-Sn-Mo-As-F and Au-Te-Bi-W granite-related deposits; skarns, greisens, HT hydrothermal veins); 3) post-Variscan (Zn-Pb, Ni-Co-As-Bi-Ag and F-Ba-Pb polymetallic and five element-type LT hydrothermal veins). The essential aspects of the district (e.g., metal contents, ore mineralogy, structural controls, cross-cutting relationships, fluid-rock reactions, timing of mineralization, formation depth, sources of elements) are under investigation by field surveys, sampling, and analytical work focused on the presence of Raw and Critical Raw Materials (RMs and CRMs) in the ores. Acquisition and digitalization from different mining archives of maps, mine reports, drilling logs, and other technical material is an essential part of the work. A specific theme involves mining waste deposits derived from past activities; sampling and analytical work point to verify their possible RMs/CRMs potential. The organization and management of data is entrusted to a specific database, to be populated with data acquired from surveys, analytical, and bibliographic work. A metallogenic thematism, partially derived from the previous metallogenic map of Sardinia (Tocco et al., 2008), with updated classifications and characteristics of deposits, is designed to display the data on the map. The final goal is to obtain a synthetic, user-friendly, and flexible structure that can serve as a prototype for applications to different geological settings and metallogenic backgrounds in Italy.

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Naitza S. et al. (2024) - Post-Collisional Tectonomagmatic Evolution, Crustal Reworking and Ore Genesis along a Section of the Southern Variscan Belt: The Variscan Mineral System of Sardinia (Italy). Minerals, 14, 65, https://doi.org/10.3390/min14010065.

Scano I. (2022) - Vein intersection zones and host rock composition as controlling factors in polymetallic ore shoots genesis: insights from the Southern Arburèse five-element (Ni-Co-As-Bi-Ag) vein system (SW Sardinia). Rend. Online Soc. Geol.It., 61, 17-26, https://doi.org/10.3301/ROL.2023.42.

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Progradation of gravelly-dominated sedimentary successions in response to orogeny accretion: a Calabrian Case

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Keywords: orogeny accretion, Calabria, Sila Piccola.

The accumulation of coarse-grained clastic successions represents a fundamental marker in the stratigraphic basins related to orogenic systems. At the southern margin of the Sila Piccola massif (middle Calabria, Southern Italy), the sedimentary archive of the middle (?) Miocene includes thick clastic successions that testify the beginning of the Calabrian Orogen growth and the progressive unroofing of its basement. Similar succession, cropping out along the south-eastern side of Sila Piccola massif, represents the so-called "Sersale clastics Formation" approximately dated to the upper Oligocene (?) - lower Miocene (Van Dijk, 1994).

In the framework of the CARG Sheet 575 "Catanzaro", such successions have been studied in detail, with the aim to connect their genesis to the tectonic evolution of the Calabrian Orogen. A detailed geological mapping, together with facies analysis, clast counts, and sandstone petrography have been carried out. The clastic unit appears to be a fluvial one, with a large variability of facies describing a meandering system,and develops with a NW-SE trending. Petrographically, most of the detritus derives from the unroofing of the uppermost plutonometamorphic layers of the Sila nappe (phyllites and granites), at that time involved in tectonic deformation related to the Calabrian Orogen growth. Locally, this plutonometamorphic signal is diluted by the presence of calcareous detritus from the Mesozoic covers, testifying the progressive thrusting deformation of these successions. All these results, combined with previous results of Servizio Geologico d'Italia (2010), would define a tectonically controlled fluvial systems transporting detritus from the Western to the Eastern part of the Calabrian area, in response to the first stages of the growth of the Calabrian Orogen.

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From geological map to geo-thematic applications: modelling susceptibility and hazard for rainfall-triggered shallow landslides for the CARG thematic map sheet F. 249 "Massa Carrara"

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Keywords: geothematic map, Alpi Apuane, landslide hazard.

As part of the CARG Italian national project, a subset of map sheets at the scale of 1:50,000 have been chosen to develop and implement geo-thematic representations that allow to demonstrate the fundamental role of geological maps in supporting the assessment of natural hazards and risk mitigation measures. This contribution describes the activities carried out for the map sheet F. 249 "Massa Carrara" located in the Alpi Apuane region (Northern Tuscany, Italy). Shallow landslides triggered during intense rainfall event represent a relevant source of hazard throughout this study area, where average mean annual rainfall locally approaches 3,000 mm/y and daily rainfall events above 200 mm/day are often recorded.

In this framework, within a scientific agreement among ISPRA, Regione Toscana administration and the University of Siena, we implemented a research programme aimed at analysing the available landslide inventories within the study area, building a new multitemporal shallow landslide inventory, and processing data to model susceptibility and hazard to landslides. To this aim, we assessed the IFFI national landslide inventory, while we performed semi-automatic classification and visual interpretation of a multitemporal set of available aerial photos spanning from 1954 to 2021 (10 epochs; 2-10 years temporal resolution) to extract a new shallow landslide inventory. Fieldwork activities allowed us to check the accuracy of the new inventory and to collect information about landslide type of movement and materials. We used both inventories to develop susceptibility models through data-driven methods: logistic regression and random forest. Moreover, we exploited the temporal information conveyed by the new shallow landslide inventory, along with a stack of 1954 – 2021 daily rainfall maps and spatial thematic data (extracted from the available CARG geology and the DEM), to model landslide hazard. This allowed us to estimate and map the return period of rainfall thresholds for shallow landslide occurrence. We present the whole set of the above described results and we show the quantitative relationships between the research outcomes and the CARG geological model to confirm the unique role of high-detail updated geological maps for natural hazard assessment and the choice of risk mitigation measures.

A possible syn-tectonic Variscan mylonitic contact between the Low- and Medium-Grade Complexes of central-northern Sardinia: new insights from the CARG Sheet "482" Bitti

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Keywords: Sardinia, Variscan tectonics.

In Sardinia, the Variscan basement is well-exposed across the whole island, wherein rocks are characterized by an increase in the metamorphic grade from southwestern (the External Zone) to northeastern (the Inner Zone) Sardinia. In central-northern Sardinia, within the area of the CARG Sheet "482" Bitti, strongly condensed Barrovian isograds are encountered. There, the transition from the low-grade chlorite and biotite zones to the staurolite+kyanite zone occurs in less than 40km. This relatively thin Barrovian domain tectonically underlies the thicker tectonic pile of the Nappe Zone. So far, this fragment of the Sardinia Variscan basement has been referred either as i) a single tectono-metamorphic domain belonging to the Inner Zone (i.e., the Low- to Medium-Grade Metamorphic Complex, Cruciani et al., 2015), or ii) two distinct domains, both belonging to the internal Nappe Zone (i.e., a Low-Grade and a Medium-Grade Complex, Carosi et al., 2020). In addition, in the geological map of Sardinia (Carmignani et al., 2016), this transept was divided into a Bt-phyllites sequence of the internal nappes and an amphibolite-facies complex to the north. Despite of the several studies carried out in the region throughout the years, a detailed geological and structural mapping is still lacking: the recent start of the Sheet "482" Bitti within the framework of the Italy "CARG" Project represents the most favorable opportunity to unravel the geological outline of the area.

In the southernmost area of the under-mapping Sheet, a monotonous pile of muscovite- and chlorite-rich phyllites with subordinate metasandstones, quartzites and metavolcanic rocks (the "Lula Phyllites") can be observed, showing a main NE-striking pervasive S2 foliation which folded a relict S1 metamorphic layering. Northeast of the Sos Enattos mine, the Lula Phyllites are apparently abruptly overthrusted onto a thick sequence of medium- to coarse-grained biotite and, subordinately, garnet-rich micaschists, plagioclase-rich metagreywackes and metavolcanic rocks, called "Onaní Tectono-metamorphic Unit". The transition marks the onset of the biotite and, in some cases, of the garnet zones. The transition can be observed as a ~100/150m thick mylonitic, NE-striking, SE-dipping shear zone cropping out south of the Lula village and east of the Sos Enattos mine. In the Sos Enattos area, the phyllites and metasandstones of the Lula Phyllites are directly in contact with (underlying) garnet-rich rocks. The similar geometry of the S2 foliation in the Lula Phyllites, in the Onaní Unit and within the mylonitic zone might be due to the possible over thrusting occurred during the D2 phase. Noteworthy, the geometry of the S2 and the mylonitic thrust are opposite to the typical geometry observed in the Nappe Zone.

Although preliminary, the so far collected data may lead to a new interpretation of the tectonic organization of the Nappe-Inner Zones transition of the Sardinia Variscan chain.

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Cruciani G. et al. (2015) - Continental collision from two perspectives: a review of Variscan metamorphism and deformation in northern Sardinia. Periodico di Mineralogia, 84, 657-699, http://doi:10.2451/2015PM0455.

Refining the stratigraphy of the Catanzaro area: analysis of two Messian conglomerate units (Calabria-Southern Italy)

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Keywords: Catanzaro Basin, Calabrian orogen, Messinian.

The Catanzaro Basin, located between the northern (Sila Massif) and southern (Serre Massif) sectors of the Calabrian-Peloritan orogen, is characterized by thick sedimentary successions showing considerable lithological heterogeneity in response to the complex tectonic evolution of the area in the Neogene. The basin is filled by a thick sedimentary succession from Middle Miocene to Messinian, included three conglomeratic units recording different exhumation phases and sea level changes. During the lower Pleistocene, it evolved, due to tectonics, to the so-called Catanzaro Strait filled by tidal transgressive succession (Longhitano et al., 2014). New geological surveys conducted in the CARG project Sheet 575 "Catanzaro", integrated by lithologically and petrographically analysis, allowed to better define the stratigraphic and sedimentological features of the conglomerate units and the tectono-sedimentary evolution of the Basin. In detail, we focus on the conglomerate units accumulated during Messinian, named Conglomerato del Riato (CR) and Conglomerato di Marcellinara (CM). The CR and CM were studied by: (i) detailed geological mapping; (ii) analysis of stratigraphic and/or tectonic relationship with the surrounding metamorphic and plutonic basement; (iii) mesoscopically sedimentary facies analysis; (iv) field clast counts; (v) microscopically characterization of matrix compositions. The lower CR received sedimentary input from the metamorphic basement that was being exhumed during that period (Malusà et al., 2015) and the gypsum successions accumulated during the first Messinian Salinity Crisis (MSC) stage (5.96-5.6 Ma). The gypsum clasts and blocks belong to the Primary Lower Gypsum as confirmed by the blocks of branching selenite facies exclusive of the first Messinian stage. The CR can be related to the Resedimented Lower Gypsum (RLG) unit (Roveri et al., 2008) deposited during the MSC acme (5.6-5.55 Ma) and related both to massive and organized processes (e.g. lamination, canalized bodies) in underwater environment. On the contrary, the upper CM shows no gypsum signature but is enriched in limestones ascribable to the Messinian Calcare di Base, in addition to the dominant metamorphic signal. This unit represents the end of MSC and can be stratigraphically correlated to the coeval Carvane Conglomerate, mainly composed of sedimentary clasts, in the Crotone Basin (Barone et al., 2008). The different petrographic compositions represent a clear difference between the two coeval basins due to the progressive exhumation of the metamorphic complex and the accumulation of sediments, and/or different paleogeographic patterns. Finally, these new data acquired during CARG project represent essential elements to define the local tectono-sedimentary evolution during MSC in the Catanzaro and Crotone Basins.

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Multi-scale study of the fracture network in carbonate rocks (Marguareis area, F. 244 – Ormea, Piedmont, Italy)

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Keywords: CARG, fractures, Marguareis.

As part of the n. 244 Ormea geological sheet (CARG project), a detailed geological and structural survey was carried out in an area of the Marguareis Natural Park, near the Don Barbera Hut. The well-exposed Meso-Cenozoic Briançonnais sequence consisting of dolomites, limestones and calcschists offers the opportunity for an in-depth structural study of the fracture network. Carbonate rocks are affected by numerous sets of faults and fractures that can be observed and traced from the outcrop- to the kilometer-scale. A quantitative characterization of the discontinuities in fractured rock cliffs has been made combining field-based investigations with satellite images and Unmanned Aerial Vehicles (UAVs) digital photogrammetry, supporting the collection of a large datasets to assess small- and large-scale fracture intensity and rock mass heterogeneity across the different lithologies. We investigated the scale-variant geometry and orientation of fault and fracture patterns, and the variation of both fracture density (P20) and intensity (P21) among the carbonate rocks, also in relation to the structural position with respect to the main faults and folds. Main question is whether and where to draw the line between the (apparently?) stochastic distribution, usually attributed to small-scale patterns, and the large-scale geologically coherent fractures, which are more predictable in relation to the regional geological context. By reversing the question, the research allows to improve our knowledge on how to treat the fracture network data to derive useful information and define the deformation evolution of the study area. In this view, the large structural dataset indicates that the Oligo-Miocene evolution of the Marguareis area developed within a mega left-lateral shear zone.

Geological mapping and electrical resistivity methods for the structural interpretation of the Pleistocene Pantano di San Gregorio Magno basin (SA)

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Keywords: geological mapping, electrical resistivity tomography, Irpinia Fault System.

The sheet 469 "Muro Lucano" includes the central sector of the Campania Lucania Extensional Fault System (CLEFS; Brozzetti, 2011), consisting of a set of NW-SE trending normal faults, particularly well exposed in the Monte Marzano area. Here, the Pantano di San Gregorio basin, located at the southeastern termination of the seismogenic Irpinia Fault, consists of a Pleistocene graben, filled with alluvial and lacustrine syn-tectonic deposits. The Irpinia fault represents a key element, as it is part of the composite seismic source Irpinia-Val d'Agri (according to the DISS 3.3.0 database), which was responsible for both the 1980 Irpinia earthquake (Mw 6.9) and the 1857 Montemurro earthquake (Mw 7.0).

In this area, corresponding to the epicentral region of the 1980 earthquake, geological mapping carried out for the realization of the 469 "Muro Lucano" sheet has been complemented with the acquisition of Deep and shallow Electrical Resistivity Tomographies (ERT), to reconstruct the overall geometry of the tectonic structures bounding the Pantano di San Gregorio Basin.

Geological mapping has been conducted by using an upgraded stratigraphic scheme when compared to the existing cartography (the 1:100.000 S. Angelo de' Lombardi, Eboli and Potenza sheets of the Italian Geological Survey) allowing a detailed reconstruction of tectonic structures. The S. Gregorio Magno basin is mostly bounded by Jurassic to Cretaceous carbonates of the Apennine Platform, tectonically covered by Cenozoic varcolored clay of the Sicilide Unit. Pleistocene marine sands and Quaternary slope breccia cover the carbonates. The basin infill consists of lacustrine shale and silt of middle-late Pleistocene age (Aiello et al., 2007). Shallow ERT surveys, conducted across confirmed or inferred fault traces, provided a detailed image of the near-surface fault architecture along the margins of the Pantano basin, highlighting lateral resistivity variations correlated with fault zones and tectonic activity. Deep ERT surveys contributed to reconstructing the subsurface stratigraphic setting in the central part of the basin, providing insights into the geometry of the bedrock and the tectono-sedimentary evolution of the graben.

The integration of the new geological survey and the geophysical data allowed the refinement of the geological and structural model of the area, with particular emphasis on the evolution of the normal faults bounding the Pantano di San Gregorio basin. This will provide a better understanding of the structural and seismotectonic setting of the region and will define the geometry of the tectonic structures associated with the Irpinia fault system, offering valuable information for seismic hazard assessment, and supporting future multidisciplinary research in the area.

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PyMeshIt: A Python-Based Platform for Geological Mesh Generation and Surface Intersection Analysis

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Keywords: meshes, geomodelling.

Tetrahedral meshes are a fundamental requirement for numerical geological modelling, providing a flexible method to discretize the modelling domain in the presence of complex structure, and are therefore simulating complex subsurface processes**.** In this study, we present PyMeshIt, a Python-based library developed to integrate the robust meshing capabilities of the C++ MeshIt software into the Python-centric PZero geomodelling platform. PyMeshIt is basically a Python wrapper to C++ MeshIt algorithms, allowing a more accessible approach for analyzing and meshing complex geological structures.

The Pymeshit workflow commences with computing convex hull, coarse segmentation, and efficient surface-surface intersection detection utilizing spatial subdivision (octree) techniques and precise triangle-triangle computations. It systematically identifies, clusters, and integrates triple points, ensuring topological consistency where multiple features converge. Intersection polylines are subsequently aligned to surface boundaries (convex hulls) and refined to a user-defined resolution, establishing high-fidelity geometric constraints. Building upon this detailed geometric characterization, PyMeshIt performs constrained Delaunay triangulation of the geological surfaces. This crucial step employs a DirectTriangleWrapper interfacing with the Triangle library, featuring a C++-linked refinement callback that strictly honors the defined intersection and boundary constraints. Mesh quality and element sizing are controlled via gradient-based refinement rules. This process, facilitated by the new Python wrapper, culminates in the generation of high-quality, watertight, feature-conforming surface meshes.

Leveraging Python with NumPy for numerical efficiency, the PyMeshIt workflow can be run from the command line or with a dedicated GUI allowing intuitive user interaction. In addition, PyMeshIt allows including those functionalities directly into the PZero GUI, with a seamless workflow from geological modelling to the creation of a watertight boundary representation, and eventually to tetrahedral meshing.

Reconstructing the basin for a 3D geological model in urban areas: a case study from CARG Programme, sheet 275 Firenze

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Keywords: 3D geological models, gravimetry, CARG.

A 3D geological model of the Quaternary deposits in the urban area of Florence is under construction as part of the development of the CARG Sheet 275. The deposits modelling starts from a plausible geometry of the top of the substrate. This surface represents the base of the 3D geological model which is bounded on the top by the surface (DTM). The reconstruction process was carried out by integrating gravimetric data (provided by ENI under an agreement with ISPRA, ISPRA, ENI, 2020) with boreholes data, more than 2,000 stratigraphic logs coming from different sources (Regional Tuscan Administration, Florence Municipality, ISPRA L.464/84), structural setting and surface geology. This process enabled the reconstruction of a surface featuring: a detailed, masked, morphology that supports the geological interpretation of the entire area. Among the main hidden morphologies, paleo drainage directions can be identified—disconnected from the current configuration and incised into the substrate—along with morphological evidence of structures and a system of "highs and lows" that shape the surface beneath the sedimentary infill. The modelling was performed using a combination of 3D modelling software (Leapfrog® Geo), GIS tools and specific processing of geophysical data carried out using MATLAB® (Salimi & Motlagh,2012). The aim of this work is to present the applied workflow, highlighting its advantages, challenges, and the results obtained. The resulting surface confirms and updates the previous reconstruction of the substrate geometry within the urban area (i.e. Moretti, 1942; Coli, 2022) and is used as the foundation for modelling the Quaternary infill deposits in the urban area of Florence, the southeastern sector of the Florence–Prato–Pistoia intermontane basin.

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The Stilo Unit in Southern Calabria: Geological Map and palaeogeographic significance

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Keywords: Stilo Unit, geological mapping, palaeogeography.

We present the geological map at a scale of 1:20,000 of an about 20 Km^2 area surrounding the village of Stilo along the Monte Consolino – Monte Mammicomito ridge in Southern Calabria. In this area, carbonate rocks of Mesozoic-Oligocene age, belonging to the so-called Stilo unit, form sparse outcrops that are markedly underinvestigated. The carbonates (Monte Mutolo formation) rest non-conformably on the Hercynian low-grade metamorphic basement, and are herein ascribed to the Tithonian (Upper Jurassic), due to the presence of *Ellipsactinia* and *Campbelliella*. This formation in the Stilo area, in contrast to the type area (Roda, 1965), is characterised by three lithofacies:

- Limestone with *Ellipsactinia*, corals (thamnasterioid, phaceloid, meandroid massive, and cerioid colonies), stromatoporoids, nerineid gastropods and rudists (diceratids), indicating a bioconstructed margin;
- subtidal muddy/peloidal lithofacies with large oncoids;
- bioclastic grainstone with ooids, echinoderms, and benthic foraminifera, suggesting higher-energy shoal conditions.

This formation is covered in paraconcordance/disconformity by the Oligocene limestones of the Pignolo formation, made of thin- to flaser-bedded pink/grey calcarenites with orbitoids, bryozoans, molluscs and red algae. The Tithonian/Oligocene boundary is locally marked by bauxites. Both the Jurassic and the Oligocene units cover the basement throught a low angle contact. In localities where the contact is best exposed, it is marked by a thin Fe-rich lateritic paleosoil. The Upper Jurassic-Oligocene carbonates are in turn unconformably overlain by the Capo d'Orlando formation. Geological mapping has revealed the presence of normal faults dissecting the Meso-Cenozoic platform, generating a complex submarine paleotopography. The faults are sealed by the flysch and are now rotated. The drowning of the Oligocene platform is elsewhere documented by the gradual increase in the siliciclastic component as the final demise of the benthic factory is marked by grey shales. The Tithonian age of the Stilo carbonates is an indication that marine flooding over the Hercynian continent was delayed with respect to N Calabria (Hettangian/Sinemurian), where the upper part (upper Jurassic/lowermost Cretaceous) of the Longobucco Basin succession hosts resedimented deposits with shallow-water carbonate grains, indicating sourcing from a productive shelf. Interestingly, the early Middle Jurassic age of the marine transgression over the Palaeozoic mainland in E Sardinia falls inbetween the two Calabrian examples, and the composition of its Tithonian interval (coral/stromatoporoid/Ellipsactinia-dominated platform rim, locally associated with ooids) is remarkably similar to Stilo. In the hypothesis that the E Sardinian and Calabrian Jurassic carbonates were produced along the same continental margin, with the Longobucco succession documenting a deeply subsiding rift basin, the Stilo and E Sardinia carbonates would indicate rift-shoulder conditions, the Stilo area being the most proximal basin-margin setting.

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Mapping the foredeep basin of the Ligurian Alps: the Moglio Testico unit (CARG Ormea sheet 244)

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Keywords: geological mapping, Italian CARG project, Flysch Units of western Liguria.

This work presents a new investigation of the Moglio-Testico (MT) tectonic unit combining geological mapping and structural analysis to aimed at better definition of the tectonic setting and geological evolution of the Ligurian Alps. The MT unit is part of the Ligurian Domain which includes remnants of oceanic and transitional crust derived from the Ligurian-Piedmont Ocean, closest to the European Margin (Vanossi et al., 1986).

The study area has been poorly studied to date, is located north of the two villages of Pieve di Teco and Vessalico (Western Liguria - Imperia province) and is comprised in the CARG Sheet n. 244 "Ormea" at 1:50.000 scale.

The MT unit is part of the "Flysch Triangle" or "Flysch Zone of Western Liguria," which consists of tectonic units distributed across Western Liguria and part of Piedmont, straddling the French-Italian border. These tectonic units are generally composed (in ascending stratigraphic order) of:

- Basal complexes, consisting of fine-grained turbiditic deposits with a stratigraphic range spanning from the Early to Late Cretaceous;
- Calcareous and arenaceous turbiditic sequences, deposited during the Late Cretaceous to Early Eocene, indicative of deep-marine sedimentary dynamics (Mueller et al., 2020; Di Giulio, 1988).
- The Flysch torbiditic sequences were deposited in foredeep or trench-like basins along the evolving Alpine-Apennine margin.

This study has resulted in: I) a detailed description of the main lithological, stratigraphic and structural features of the study area; II) a QGIS-based digital geological map with associated database; III) an new interpretative structural map at 1:10,000 scale; IV) three geological cross-sections representing the most salient tectonic features of the mapped area. The interpretation phase included a comparative analysis with of the stratigraphic and tectonic contacts delineated in the "Geological Map of the Units Between the Ligurian Briançonnais and the Helminthoid Flysch" by Boni & Vanossi, (1972).

This new advancement in knowledge of the area was made possible thanks to funding from the ISPRA-CARG project "Ormea" sheet 244 (2022-2026).

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Submerged coastal systems along the Western Sardinian shelf (Mediterranean Sea)

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Keywords: submarine depositional terrace, barriers, sea level rise, meltwater pulses, Holocene.

The results of the underwater geological and geophysical survey of the seabed of the continental shelf of the western Sardinian margin (Mediterranean Sea, Italy) carried out as part of the production of sheet 546 (Guspini) of the Geological Map of Italy 1:50,000 (CARG project) are presented. The focus of the study was to provide evidence of the various submerged coastal systems, beach barriers, submerged depositional terraces (SDT), submerged dunes and the current infralittoral prograding wedges (IPW) associated with the last eustatic cycle.

The activity was carried out by interpreting multibeam echosounder data, side scan sonar photomosaics, reflection seismic data and aerial orthophotos. A total of 48 sediment samples were collected and analysed to validate the interpretation data.

The continental shelf of the study area is characterised by the presence of a Cenozoic sedimentary basin filled with Miocene and Pliocene sediments. Interpretation of the new seismic data seems to indicate the presence of normal faults that have affected the sedimentary sequence, which has been assigned a Pliocene age. The Quaternary sedimentary cover is of limited thickness and is the result of fluvial contributions from the River Tirso (from the north) and the rivers of the Arburese region (from the east) during low sea level. During the Late Pleistocene-Holocene rise of the sea-level, submerged coastal systems were formed and preserved along the shelf.

A series of SDTs are present at different depths (between -150 and -40 m), indicating phases of slowing of the rate of sea-level rise that allowed the formation of depositional terraces. The depositional and progradational nature of the STDs is evident from the stratigraphic pattern revealed by the seismic sections.

Associated with the STDs are submerged barriers and cemented parabolic dunes between -65 m and -30 m depth. A distinct submerged coastal system was mapped at ~65 m depth. Considering both location and elevation, this submerged system is interpreted to have formed during a period of relative slowdown of the rate of sea-level rise between Melt Water Pulse (MWP)-1A and MWP-1B.

The morpho-bathymetric, stratigraphic and sedimentological data used for the submarine mapping of CARG sheet 546 indicate the presence of extensive and well-preserved submerged coastal systems, compatible with a pulse model of sea-level rise.

Plio-Quaternary contractional tectonics along the Gonfolite Backthrust (Southern Alps, n.74 "VARESE" Geological Sheet – CARG Project)

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Keywords: European Southern Alps, active faults, CARG Project.

The Gonfolite Backthrust is a major north verging shallow structure that has accommodated contraction during the Rupelian-Miocene at the margin of the Gonfolite Lombarda Gr. clastic wedge, resulting in a younger-on-older thrust. Syn-contractional deposition in a deep-sea fan environment resulted in a fanning depositional geometry, with older strata dipping up to 60o and younger units less dipping and progressively onlapping.

The age of the more recent growth of the Gonfolite Backthrust is debated. Syn-contractional deposition is up to Tortonian in age whereas other folds and thrusts nearby are apparently sealed by the Messinian (i.e., Pontegana Conglomerate). Nonetheless, several lines of evidence point to a more recent re-activation of the structure, including: i) deformed late Zanclean marine clays along the thrust; ii) pinched and deformed glacial and glaciolacustrine units near Como downtown (Livio et al., 2009); iii) Holocene reverse faults along the westernmost sector of the Gonfolite Backthrust (Menegoni et al., 2023).

Even if the listed works strengthen the interpretation of the Gonfolite Backthrust as an active and capable fault, the picture drawn so far leaves a gap in the documented history of the structure between Early Pliocene and Late Glacial – Holocene.

In the framework of the geological mapping of the n.74 "VARESE" Sheet (CARG Project), we here describe in detail a new outcrop where a lower-middle Pleistocene sequence (i.e., Allogruppo della Colma) is faulted along the Gonfolite backthrust. We collected structural measurement and analyzed a 3D virtual outcrop in order to better document the deformed succession.

Structural analysis and inversion of the faults indicate a strain field perfectly consistent with the movement of the outcropping fault plane, whereas glacio-tectonics can be ruled out.

These results place a new tile in the puzzle of the activity of the Gonfolite Backthrust, demonstrating that, after the main Oligo-Miocene activity of the fault, a later nearly continuous phase of activity spanned from Early Pliocene to Holocene.

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Menegoni N. et al. (2023) - Holocene deformations at the Po Plain–southern Alps transition (Lake Maggiore, Italy): inferences on glacially vs. tectonic-induced origin. Geosciences, 13(9), 286.

Structural Inheritance from rifting to contractional tectonics: first results from the n.74 "Varese" Sheet, CARG Project

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Keywords: European Southern Alps, structural inheritance, CARG Project.

In the framework of the geological mapping of the n. 74 "VARESE" Sheet (CARG Project), we surveyed an area bridging the transition from the Eastern to the Western Southern Alps (Scaramuzzo et al., 2022). This sector has been extensively affected by extensional tectonics during the Middle Triassic – Jurassic and major east-dipping crustal-scale listric normal faults accommodated extension resulting in the development of a sequence of basins and swells (Scaramuzzo et al., 2025). To the east, the Lugano-Valgrande Fault (Bertotti et al., 1993) marks the limit of the Generoso basin and west of it a long-lasting structural high (the Arbostora swell) occupies the central part of the area. More to the west, a narrow through is bounded by the Maggiore Line and by the antithetic Mt. Nudo Fault (Beltrando et al., 2015).

Later Alpine contractional tectonics inherited such a structural and tectonostratigraphic setting, resulting in a complex architecture of fault and folds, typical on inverted passive margins. These include: i) positive inversion of inherited and compliant faults; ii) strike slip and tear faulting; iii) the co-existence of deeply rooted structures and shallower detachment levels, iv) the local re-orientation of the regional stress field due to particularly weak inherited fault planes. We present the first results from the mapping of the n.74 "VARESE" Sheet and discuss the implications for the Alpine evolution of this sector of the Southern Alps.

Notwithstanding the complex pattern of contractional tectonic styles summarized above, we preliminarily recognized two tectonic phases characterized by a clockwise rotation of the stress field through time from ca. NNW-SSE to NE-SW (see also Scaramuzzo et al., 2022).

During our survey, we made use of virtual outcrops obtained by means of UAV photogrammetry and of UAV-LiDAR derived DTMs, allowing the collection of measurements in otherwise unreachable areas and to recognize subtle topographic changes and morphological features, even under dense tree canopy, that helped in interpreting the geology of the area.

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Bertotti G. et al. (1993) - From rifting to drifting: Tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. Sedimentary Geology, 86(1-2), 53-76.

Scaramuzzo E. et al. (2022) - Anatomy and kinematic evolution of an ancient passive margin involved into an orogenic wedge (Western Southern Alps, Varese area, Italy and Switzerland). Swiss Journal of Geosciences, 115(1), 4.

Scaramuzzo E. et al. (2024) - Transpressional tectonics during the Variscan-Alpine cycle transition: supporting a multi-rifting model, evidence from the European western Southern Alps, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-1135.

Pre to syn orogenic evolution of the European margin: clues from the Flysch units of the Ligurian Alps (CARG Project – Ormea sheet 244)

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Keywords: Ligurian Alps, Ligurian Flysch, European margin.

The project builds on the ongoing fieldwork for the 1:50.000 scale "244-Ormea Sheet" within the CARG Project framework. Some aspects of the area's evolution remain unclear, both stratigraphically and structurally. The aim is to integrate existing data to provide new insights into the evolution of the Alpine orogenesis. The study area is located in the Ligurian Alps, the southeastern part of the Western Alps. This region is crucial for understanding the geodynamic evolution of the Alps, as it preserves the contact between the Briançonnais domain (European passive margin) and Piedmont-Ligurian domain (oceanic sedimentary covers). Fieldwork has revealed a complex tectonic setting, with evidence of a polyphase tectonic evolution. These units underwent low-grade metamorphism, which partially overprinted the original sedimentary structures. This research has contributed to update existing geological maps, especially the boundaries of the Colla Domenica-Leverone unit (as referred to in the literature), which remains a debated topic. This "unit" is characterized by a basal complex consisting of thinly bedded turbidites, often containing olistostromes, known as Colla Domenica Shale, followed by a turbidite system (Decarlis et al., 2014), referred to as the Leverone Formation. These deposits are interpreted as originating from a trench environment (Di Giulio, 1992). Previous studies have proposed that these formations were deposited in an abyssal plain, resulting from the rifting and spreading of the Piedmont-Ligurian Ocean, and later involved in the Alpine collision phase during the accretionary wedge propagation. In the literature, the Colla Domenica Shale and Leverone Formation are also considered a tectonic unit. However, our fieldwork revealed an erosional boundary at the base of the Colla Domenica Shale, which differs from the previous assumption of a tectonic surface, leading us to reconsider the classification of the Colla Domenica-Leverone as a tectonic unit. Furthermore, we are investigating the origin of the sediments through XRF and ICP-MS analyses on basalt samples collected from a chaotic level within the Colla Domenica Shale. The bulk and REE composition results show similarities with those proposed by Saccani et al. (2008) for basalts outcropping in northern Corsica (Balagne region). This preliminary evidence could suggest that these formations filled the closing oceanic basin (as proposed by the Pandolfi et al., 2016 model) through mass transport events and turbidity currents, likely originating from both the accretionary wedge front and the European margin. Additionally, petrographic analyses of sandstone samples are underway to identify the source areas of the flysch formations and describe their sedimentary features. Biostratigraphic analyses have also been conducted to provide additional time constraints. Finally, we are working on stratigraphic logs and planning XRF analyses on matrix samples collected from the Colla Domenica Shale.

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Saccani E. et al. (2008) - Corsica ophiolites: geochemistry and petrogenesis of basaltic and metabasaltic saltic rocks. Ofioliti, 33(2), 187-207, https://doi.org/10.4454/ofioliti.v33i2.369.

Pandolfi L. et al. (2016) - Stratigraphic and structural features of the Bas Ostriconi Unit (Corsica): Palaeogeographic implications. C.R. Geoscience, 348, 630-640, https://doi.org/10.1016/j.crte.2016.07.002.

Late Quaternary unconformity-bounded stratigraphic units in the Verona Area (northern Po Plain)

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Keywords: UBSU, Quaternary, fluvioglacial system.

Reconstructing the subsurface architecture of Quaternary successions in glacially influenced settings is a challenging task due to the high lateral stratigraphic variability and common amalgamation of sedimentary bodies. As part of the CARG geological mapping project (Sheet 124 – "Verona Est"), we provide a preliminary interpretation of the shallowly (0-100 m) buried succession of the eastern Verona plain at the northern margin of the Po Basin, based on the identification of unconformity-bounded stratigraphic units (UBSUs) that correlate to Middle Pleistocene-Holocene interglacial-glacial cycles. The study relies on a comprehensive dataset of 667 stratigraphic and geotechnical records, which include core descriptions, groundwater wells, and cone penetration tests, integrated with a set of recently acquired continuous cores. Stratigraphic correlations were carried out using the concepts of 'event stratigraphy, with a special emphasis on the distinction between glacial and interglacial deposits. Laterally continuous peat layers that separate thick gravel and sand bodies were used as stratigraphic markers. Previous studies conducted on Late Pleistocene outcrops of the Adige Moraine Amphitheatre offer useful analogs for interpreting depositional processes and environments inferred from subsurface data. The exposed successions include glacial diamictons, stratified glaciofluvial gravels, and finely laminated glaciolacustrine deposits associated with glacial periods, as opposed to fluviolacustrine and alluvial interglacial successions. A west–east oriented stratigraphic cross-section delineates the geometry and spatial distribution of gravel/sand bodies, and sheds light on the dynamics and sedimentary evolution of the Quaternary fluvioglacial system. We demonstrate the effectiveness of a UBSU stratigraphic approach based on high-resolution subsurface data to improve our understanding of Quaternary glacially-influenced settings.

Geological mapping of the Eocene Lessini Mountains volcanic district (Veneto, Italy) within the CARG project

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Keywords: CARG project, volcanic stratigraphy, Lessini Mountains.

A new geological map is being produced for the Lessini Mountains in the Italian Southern Alps, Veneto Region as part of the National Geological Mapping CARG Project (Sheet 124 – Verona Est). The study area comprises Meso-Cenozoic sedimentary rocks, Tertiary volcanic products belonging to the Lessini Mountains volcanic district and Quaternary deposits. Mapping of volcanic rocks is performed at the 1:10.000 scale. Based on lithological features, geomorphological and petrographic data, basaltic hyaloclastites and lava flows have been recognized. Stratigraphic relationships between sedimentary and volcanic deposits show that volcanic activity started during the Eocene in submarine environments, and evolved progressively towards subaerial conditions. Preliminary observations suggest, as initial volcanic manifestation, a typical basaltic fissural eruptive activity in submarine context, while shield volcanoes prevail in the successive subaerial environment. Such volcanic structures developed in the peculiar geodynamic setting of the Venetian Volcanic Province, where volcanism interacts with (i) the pre-Eocene sedimentary succession, frequently crossed by cm- to m-thick dykes and sills, and (ii) tectonic structures (e.g., normal, high-angle faults), exploited by the rising magmas.

The experience of the CARG 245 - Albenga sheet

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Keywords: geological mapping, Western Alps, Mediterranean tectonics.

We present the results from the activities related to the 245 – Albenga sheet, located in western Liguria. The Albenga sheet encompasses both emerged (450 km^2) and marine (150 km^2) areas. The onshore survey has been performed through a traditional, field-based approach integrated with stratigraphic and structural analyses performed on Digital Outcrop Models (DOM) derived from digital photogrammetry and the use of Unnamed Aircraft Vehicles (UAV). The submarine survey is based on the integration of a new set of seismic reflection lines and high-resolution bathymetric data (MBES) with pre-existing available geological and geophysical datasets. The emerged area consists of a wide variety of rock types, including: i) Palaeozoic to Eocene metaintrusive, metavolcanic and metasedimentary sequences that experienced pre-Alpine and/or Alpine orogenic deformation and metamorphism; ii) Oligocene to Pliocene post-orogenic sediments and a large Quaternary mixed marine-alluvial fan. Geological mapping and structural analysis resulted in the discovery of new important deformation structures such as: i) a previously unreported km-scale transtensive fault zone, crosscutting the metamorphic units of the Ligurian Alps and, ii) earthquake-related soft sediments deformation structures in Miocene-Pliocene deposits (Pietra di Finale and Argille di Ortovero). The offshore area consists of a continental shelf and the upper slope both intersected by well carved submarine canyons and characterized by a complex fault network. The integration of the new onshore and offshore observations allows to propose new insights about the present-day morpho-structural setting and the post-Oligocene tectono-stratigraphic evolution of the western Ligurian Sea margin in the framework of central Mediterranean area.

The Geology of the external Irpinia-Daunia sectors: unresolved problems and new possible hypotheses for southern Apennines

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Keywords: geological issues, southern Apennines.

The external Irpinia-Daunia sector, located at the northwestern termination of the Southern Apennines, remains a region where several fundamental geological issues are still open to debate. Traditional interpretations, developed in the framework of thin-skinned tectonic models, described the area as an external frontal sector characterized by a stack of allochthonous units thrusted above the Apulian foreland during the Neogene. However, structural, stratigraphic, and geophysical data accumulated over the last two decades increasingly highlight the limitations of these models. Persistent unresolved problems include: (i) the ambiguous stratigraphic definition of several tectonic units attributed variably to Lagonegro Basin, "Argille Varicolori" Complex, Sannio Basin or Apulian Margin successions; (ii) the incomplete understanding of the kinematics and chronology of thrust emplacement, particularly with respect to out-of-sequence thrusting episodes; and (iii) the uncertain contribution of basement-involved structures to the current structural architecture.

New possible hypotheses, based on integrated field mapping, cross-sections, structural analysis, and reinterpreted seismic profiles, suggest a more complex tectonic evolution involving significant interaction between thin-skinned and thick-skinned processes. Preliminary models propose that pre-existing normal faults, developed during Mesozoic rifting, have acted as upper crustal-scale weakness zones reactivated during contraction, thus favoring localized uplift and out-of-sequence thrusting. The analysis of syn-orogenic deposits within thrust-top basins indicates a high degree of deformation partitioning and diachronous thrust activity between the Late Miocene and Early Pliocene.

Moreover, detailed stratigraphic and structural data suggest the possibility of differential involvement of the Apulian carbonate platform and basin sequences, leading to complex lateral variations in structural style and thrust stacking geometries. These features are not adequately captured by classical models that assume laterally homogeneous mechanical stratigraphy and thrust wedge propagation.

The ongoing new geological surveys (within the activity for the CARG sheet 420 "Troia" in the frame of the external Irpinia-Daunia area) points toward a polyphase, spatially heterogeneous orogenic evolution, with significant implications for the tectonic reconstruction of the Southern Apennines front. Addressing these unresolved issues will require further high-resolution field studies, targeted geophysical investigations, and advanced structural modeling to constrain the relationships between inherited structures, syn-tectonic sedimentation, and neotectonic reactivation. The external Irpinia-Daunia region remains a crucial sector for testing competing geodynamic models of foreland fold-and-thrust belts and assessing active tectonics in an area with a long history of seismicity.

Sheet 377 "Trasacco" of the Geological Map of Italy at 1:50,000 Scale: new insights about the geological and tectonic evolution of the Roveto Valley

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Keywords: CARG project, geological mapping, Central Apennines.

Here, we present new insights from the 1:50,000-scale CARG 377 "Trasacco" geological sheet. The study area is located in the axial part of the Central Apennines, along the border between Abruzzo and Lazio regions. It includes the easternmost portion of the Simbruini-Ernici ridge, the Roveto Valley, the westernmost part of the Marsica Region and the southern sector of the Fucino Plain. Fieldwork was conducted using traditional methods combined with modern instruments and techniques, following the guidelines of the CARG Project. Portable devices (tablets and smartphones) equipped with specific software (QField, https://qfield.org/) allowed for on-field digital mapping of georeferenced areal and linear elements, as well as the collection of georeferenced photos. The general stratigraphy of the study area consists of Meso-Cenozoic carbonate deposits, overlain by upper Miocene-Pliocene terrigenous deposits. Along the SW margin of the Roveto Valley, the Simbruini-Ernici thrust front juxtaposes Meso-Cenozoic carbonates above Messinian sandstones and marls; conversely, the NE margin is bounded by a SW-dipping normal fault, belonging to the extensional system of the Central Apennines, characterized by a polyphase tectonic history. While our findings enhance previous research and studies, they also raise new questions that could influence the reconstruction of the geological and tectonic evolution of the Roveto Valley. Specifically, field mapping revealed the presence of valuable geological and geomorphological features, some of which were previously documented (Parotto, 1969; Cavinato et al., 2012; Fabbi & Smeraglia, 2019; Fabbi et al., 2023), but their geometrical relationships, spatiotemporal evolution, and/or origin were not fully understood. An example is provided by the Messinian Val Roveto siliciclastic basin, for which a redefinition of the stratigraphic, paleotectonic, and paleogeographic context was achieved through the integration of field and subsurface (seismic) data. Another significant finding is the redefinition of the Civita d'Antino "Mesozoic" outcrops, previously interpreted as a klippe but now identified as the remnants of a large Quaternary landslide originating from the steep slopes of the Marsica ridge. Moving forward, future work will focus on more detailed stratigraphic, sedimentological, and structural analyses to better reconstruct the evolution of the study area. These efforts will contribute to a deeper understanding of the geological history of this complex sector of the Central Apennines.

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Plio-Quaternary evolution of the Strait of Messina area (southern Italy)

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Keywords: CARG project, Calabrian Arc, active tectonics.

Geological data collected in the area of the Strait of Messina (Southern Italy) in the frame of the CARG project (Sheet n. 588 – Villa San Giovanni), together with previously published geomorphological and geophysical data (Monaco et al., 1996; Ferranti et al., 2008; Aloisi et al., 2012; Barreca et al., 2021), refine the knowledge on the Plio-Quaternary evolution and the seismotectonics of the area. This marine passage, connecting the Tyrrhenian Sea to the Ionian Sea, is located within the Calabrian Arc, a seismically active region whose regional tectonic setting is controlled by the rollback of the subducting Ionian slab. In particular, the strait developed in the axial sector of a large extensional basin resulting by the activity of a system of ~NE-SW trending faults during the Upper Pliocene-Pleistocene times. The interplay between faulting and regional processes produced differential vertical movements across the area, with subsidence in the Strait and uplift in the surrounding coastal areas, as also evidenced by raised marine terraces. Quaternary deposits outcropping in both sides of the Strait are mainly composed of siliciclastic deposits, including deltaic-marine sediments (i.e., the Middle Pleistocene Messina Formation) and marine terraces. These latter have been uplifted and faulted over time. Current tectonic activity makes the Strait of Messina one of the most seismically hazardous areas in Italy. It has been the source of significant historical earthquakes, including the devastating M~7.0, 1908 Messina earthquake. Seismogenic structure have been detected on land (e.g., the Scilla and Armo faults) and within the Straits (e.g., the W-fault). This latter has been clearly revealed by high resolution seismic lines in the offshore along with displaced Quaternary marine terraces on land and point to active deformation along a previously unmapped ~34.5 km-long extensional fault. Finally, a new seismic tomography and crustal-to-subcrustal scale 3D-modelling strongly suggest a cause-and-effect relationship between the Ionian slab retreat, mantle wedging, uplift in the upper plate block, and active extension in the Strait of Messina area.

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A metamorphic belt modelling approach: the Structural Topology model

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Keywords: 3D modelling, topology, structural topology model.

3D geological modelling in polydeformed metamorphic belts remains a significant challenge due to the structural complexity and the limited applicability of time-aware methods. In such settings, the difficulty lies not only in surface interpolation techniques but also in the geological and topological meaning assigned to each boundary. We propose a modelling strategy that combines conceptual surface and volume labelling and topological analysis to reconstruct robust geological legends and to ensure consistent 3D structural models.

Our approach can integrate explicit and implicit modelling techniques, using conceptual surface and volume labelling. Geological units (i.e. volumes) are classified as stratigraphic (S), tectonostratigraphic (TSU), tectonometamorphic (TMU), intrusive (IU) or shear zone (SZ), depending on their origin and deformation history. Geological boundaries (i.e. surfaces) are characterized in relation to their spatial and functional role within larger tectonic domains. A structural framework based on polarity vectors and tectonic position is adopted in the absence of absolute or relative age constraints, enabling the application of time-aware interpolation even in complex metamorphic settings.

While it is being translated into a consistent 3D framework, our methodology has been designed so that the geological reasoning typically used in 2D mapping is preserved, such as stratigraphic ordering, interpreted boundaries, cross-cutting relationships and domain correlation. In this context, a Structural Topology model (STm) is developed, emphasizing the hierarchical role of surfaces in space and time. This preserves topological consistency, allowing seamless translation into volume meshes and integration into volume-based modelling environments.

The workflow presented here enhances interpretability, reproducibility and conceptual robustness by ensuring that geological and topological information is coherently embedded, particularly in metamorphic settings. The proposed strategy supports a more reliable 3D geological modelling practice, enabling subsequent geoscientific analyses and applications in structurally complex regions, highlighting the benefits of combining surface- and volume-based modelling.

The 3D geological model of the CARG 121 Brescia 1:50,000 sheet: insights into the evolution of the Southern Alps fold-and-thrust belt

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Keywords: 3D geological model, Brescia geological sheet, fold-and-thrust belt.

The 121 Brescia sheet (1:50,000 Geological Map of Italy) spans from the Southern Alps to the seismically active northern Po Plain. This area features faulted and folded Mesozoic–Cenozoic carbonates in the Alpine sector, and Quaternary marine, fluvial and glacial deposits in the foreland, affected by recent tectonics.

Intensive exploration for hydrocarbons, groundwater resources and scientific research has yielded a large subsurface dataset and the construction of 3D geological models. Thanks to ISPRA, Regione Lombardia, ENI, A2A Ciclo Idrico, and AATO Brescia, much of this data was made available for 3D geological modelling. The dataset includes seismic profiles, hydrocarbon and water well logs, gravimetric data, Airborne Electromagnetics (AEM), and analyses from shallow cores. Stratigraphic and structural data from the CARG detailed field survey, especially in the Alps sector, further complemented the data for the 3D modelling.

All datasets were processed in specialized software and imported into a 3D GIS to model geological surfaces and volumes, offering an integrated view of the subsurface geology. The 3D model extends from the topographic surface down to about 8,000 m below sea level and includes 10 major thrusts and back-thrusts. These faults displace seven stratigraphic surfaces separating informal groups of litostratigraphic units and depositional sequences spanning from Late Triassic to Holocene.

The modelled faults are part of the Southern Alps fold-and-thrust belt formed during the Alpine compressive phase, which is characterized by two distinct kinematic stages in the CARG 121 Brescia sheet area. The first stage was characterized by a southeast-directed transport along NNE-SSW-striking faults. The second compressive stage is defined by south-directed transport along E-W structures. During this latter phase, the NNE-SSW structures acted as transfer faults with sinistral transpressive movements. The cross-cutting relationships among these faults and the tectonic transport directions suggest a change in the direction of maximum horizontal stress during the Alpine compressive phase documented in the CARG 121 Brescia sheet, from approximately NW–SE to N–S.

The youngest tectonic structure that characterizes the subsurface of the area is the southward-dipping, E-W-striking Castenedolo back-thrust. This fault generates a broad fault-propagation fold deforming the Quaternary (Middle Pleistocene) sedimentary succession exposed along the Castenedolo and Ciliverghe hills, affecting the recent sedimentary architecture of the alluvial plain. The geological 3D model shows that the Castenedolo back-thrust originates from the underlying Malpaga thrust, which, together with the more internal and shallower Chiari, Borgosatollo, and Brescia thrusts, defines the structural framework of the Alpine chain buried beneath the Po Plain.

Data acquisition techniques and preliminary results obtained during mapping of the 491 Ferrandina sheet (CARG project, Basilicata)

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Keywords: Bradanic foredeep, data acquisition method, geological mapping.

The geological mapping of large areas, such as those acquired in the frame of the CARG project, is an opportunity to introduce new methods for an accurate data acquisition and the interpretation of peculiar landforms occurring in the area. In the context of the Ferrandina sheet n.491, a multidisciplinary investigation approach was adopted, associating to classical fieldwork, the use of satellite images and aerial photos.

The study area is located in the province of Matera (Basilicata), where three important NW-trending valleys (Bradano, Basento and Cavone valleys) cut the siliciclastic deposits of the Pleistocene Bradanic foredeep, locally affected by minor extensional faults (Bentivenga et al., 2014). A major complexity of the area is represented by the presence of different generations of late Pleistocene to Holocene deposits, represented by alluvial and landslide deposits, formed during the progressive uplift and erosion of the foredeep deposits.

The stratigraphy of the area includes: the Altamura Limestone Formation (upper Cretaceous), unconformably covered by the Gravina Calcarenite Formation (Lower Pleistocene), representing the top of the Apulian platform. These are superimposed by the foredeep succession, made up of the Argille Subappennine Formation (Calabrian) and by sandstone and conglomerate of the San Marco and Fosso Macello formations, that instead indicate the closure of the Bradanic Foredeep during the middle Pleistocene. The acquisition of the survey data has been performed with a functional algorithm realized for the QField app connected to the free QGis software. This allowed to report georeferenced descriptions of the identified outcrops, linking the attitude symbology to the relative formation icon. The stratigraphy of the Argille Sub-Apennine was measured with Jacob's staff and sampling 5 m for the dating of nanoplankton. For the coarse-grained San Marco succession, we sampled a volcaniclastic level of inferred middle Pleistocene age (Corrado et al., 2017), occurring in the upper part of the formation, for isotope dating. The identification of landslide and terraced deposits represented a major issue for the geological mapping. This is caused by scarcity of exposures, which limited the direct identification of these deposits in the field. To this end, we used mostly aerial photos and satellite images. In addition, landslide deposits may be differentiated into ancient, characterized by the presence of heterometric blocks in sandy-clayey matrix, and recent landslides, mostly represented by earthflow. To better identify active landslides, we used remote interferometric synthetic aperture radar (InSAR) technique, which allows to capture possible movements in high spatial and temporal resolution in different cloud conditions. Using data acquired by Copernicus Sentinel-1 from 2016, InSAR was applied on the northern slopes of Ferrandina, allowing to observe very slight movements that justify more or less deep gravitational phenomena.

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Corrado G. et al. (2017) - Constraints on the dispersal of Mt. Vulture pyroclastic products: implications to mid-Pleistocene climate conditions in the foredeep domain of southern Italy. Géomorphologie: relief, processus, environnement, 23, 22025, https://doi.org/10.4000/geomorphologie.11731.

Geological mapping of turbidites for the CARG Project: methodological challenges and solutions from a review of CARG mapping of the Latium-Abruzzi "turbidite complex", central Apennines (Italy)

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Keywords: geological mapping, turbidites, CARG.

The Latium-Abruzzi "turbidite complex" (here referred to as LAT) extends along a NW-SE band around 50 km wide and over 150 km long in the central Apennines, from the Salto Lake to the northern part of the Campania region. It is interpreted as the Tortonian-Messinian fill of the NE-migrating foredeep of the Apennine chain. The system extends over at least 20 CARG sheets from 348 "Antrodoco" in the north, to 416 "Sessa Aurunca" in the south. Publication dates vary from the 1970s (e.g. 389 "Anagni") to the 2020s (e.g. 348 "Antrodoco"). Around 1/3 of the CARG sheets are not published yet and they are under different statuses of completion. The extent of the turbidite deposits is generally unambiguous in the field and it was already detailed by the Italian official geological maps 1:100,000 published until the 1960s. Starting in the 1970s, an effort has been made by the CARG project to differentiate the turbidite deposits into a number of distinct units. Because of the lack of recognised units with a chronostratigraphic significance, the distinction has been based mainly on lithology and sedimentary facies.

As part of the research work in support of the geological mapping of the sheet 390 "Frosinone" which is currently ongoing, a review of the methodologies applied in the mapping of the LAT has been undertaken for the published maps of the CARG Project. For each map, the methods used to subdivide the LAT in a number of distinct units have been extracted and compiled as a table. The methodologies are generally based on the use of facies associations, with the thickness of the sandstone layers and the overall sandstone to pelite ratio being the two most important criteria. A general classification based on a combination of all the classification criteria has been devised and applied to the different maps by creating a series of conversion charts. Finally, the mapped units converted to the general classification have been integrated into one single combined map. The final map is consistent throughout, hence indicating the overall value of the mapped units and of the individual classification schemes. However, this exercise highlighted how cumbersome is such an attempt at integrating between maps. Additionally, because different approaches have been employed for different sheets, this results in abrupt changes across map boundaries. Two key challenges in the definition of the units were highlighted by the review: i) how to set the size of the area used for averaging the recognition of an individual facies association ii) how to maintain consistency across areas with different outcrop quality.

This contribution aims to stimulate a discussion within the CARG Project, leading to a common methodological framework for mapping the LAT and more generally turbidite deposits, which could be applied in the making of maps that are not published yet and when updating maps already published.

Revisiting the Montello thrust (Venetian prealps, NE Italy): evidence for segmentation from the geological mapping of the Vittorio Veneto sheet in the framework of the CARG project

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Keywords: seismic interpretation, Montello structural model, Eastern Southern Alps.

As part of the CARG Project (Sheet 084 – Vittorio Veneto), we present the preliminary structural model for the Montello area, which highlights the segmentation of the Montello Thrust, interpreted by Galadini et al. (2005) as a continuous 30 km long structure able to release Mw 6.7 seismogenic potential. Within the Venetian Prealpine domain, The Montello-Conegliano Thrust represents the outermost front of the eastern Southern Alps (ESA), a SSE-verging fold-and-thrust belt developed since the Neogene, in response to the convergence between the Adria and European plates. In this sector, the ESA front is composed by SW-NE trending arcuated thrust systems which cause the progressive deformation and southeastward overlapping of the Miocene and Pliocene sequences on the Quaternary units of the northern Venetian Plain. The strongest earthquakes of the area, which include the Mw 6.4 Asolano 1695, the Mw 6.3 Alpago 1873 and the 1936 Mw 6.1 Cansiglio earthquakes (CPTI15 catalogue v4.0, Rovida et al., 2022), are located in the inner sector of the belt, north of the Bassano-Cornuda, Valdobbiadene-Vittorio Veneto and Cansiglio Thrusts. In this regard, Barba et al. (2013) interpreted the Valdobbiadene-Vittorio Veneto Thrust as a locked structure capable of generating large earthquakes, while the Montello Thrust is thought to accommodate deformation primarily through aseismic creep. The structural model recently proposed by Picotti et al. (2022) is consistent with the seismotectonic behavior of the regional structures, but still defines the Montello Thrust as a single buried fault extending for approximately 30 km and approaching the surface just north of Treviso.

Based on the interpretation of a seismic dataset (ENI and British Gas seismic lines), calibrated with well logs, we reconstructed the buried architecture of the area. The collected subsurface data were also integrated with field data acquired during the geological survey conducted within the CARG Project for the realization of the Vittorio Veneto geological map. The proposed structural model, supported by the collected results, suggests that the Montello Thrust does not form a single continuous fault but is instead segmented into distinct portions (the Montello-Arcade and the Conegliano Thrusts), each 10-15 km in length.

This structural segmentation has significant implications for the seismic hazard assessment of the area, as the presence of smaller seismogenic sources reduces the maximum expected earthquake magnitude, aligning with the lack of major seismic events recorded in the Parametric Catalogue of Italian Earthquakes (CPTI15 v4.0) for the area.

Barba S. et al. (2013) - Modeling the interseismic deformation of a thrust system: seismogenic potential of the Southern Alps. Terra Nova, 25(3), 221-227, https://doi.org/10.1111/ter.12026.

Galadini F. et al. (2005) - Seismogenic sources potentially responsible for earthquakes with M ≥ 6 in the Eastern Southern Alps (Thiene-Udine sector, NE Italy). Geophys. J. Int., 161, 739-762, https://10.1111/j.1365-246X.2005.02571.x.

Rovida A. et al. (2022) - Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 4.0. Istituto Nazionale di Geofisica e Vulcanologia (INGV), https://doi.org/10.13127/cpti/cpti15.4.

Picotti V. et al. (2022) - The Montello Thrust and the active mountain front of the Eastern Southern Alps (Northeast Italy). Tectonics, 41, e2022TC007522, https://doi.org/10.1029/2022TC007522.

Geological mapping of submerged areas of the "Torretta Granitola - Pantelleria" CARG sheet (n. 626)

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Keywords: CARG Project, submerged areas mapping.

The new phase of the CARG Project, started in 2020, allowed to undertake several geological surveys of submerged areas. Among them, the Geological Survey of Italy is realizing, in collaboration with other research institutes and universities, the geological map of the sheet n. 626 "Torretta Granitola-Pantelleria" including onshore and offshore areas of Pantelleria Island, a small, emerged area in the surroundings of Capo Granitola (Sicily) and an extended submerged area offshore the southern Sicilian coast.

The geological survey onshore Pantelleria Island has been recently completed, whereas surveys of the submerged area are still ongoing.

Data in submerged areas are acquired by indirect surveys carried out by geophysical methods groundtruthed by samplings, video inspections or scuba diving. Geophysical acquisitions consist of high resolution multibeam surveys and sub-bottom profiler seismic reflection data. Due to the presence of a morphologically articulated seafloor, with sudden changes in depth values, backscatter data by multibeam surveys were preferred to sidescan sonar acquisitions.

The sub-bottom profiler data showed very poor substrate penetration, preventing clear identification of reflections. This information allows to suppose that the seabed is almost entirely characterized by hard volcanic rocks, presumably lavas, according to what has been recognized on land.

Two meters resolution DTM obtained from geophysical acquisitions was analyzed together with the high-resolution DEM of emerged areas, allowing a preliminary correlation between the structures identified in submerged areas and the depositional units identified on land (lava flows and ignimbrites as well as tectonic lineaments)

Further surveys of submerged areas, particularly along the southern Sicilian coast, are still needed to address and evaluate the nature and extent of phanerogams meadows.

Quantitative Characterization of Fracture network in large sheath-fold: field and UAV-based Digital Outcrop Model analysis (CARG Project 245-Albenga)

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Keywords: poly-deformed rocks, digital outcrop model, fold-fractures relationship.

Predictive models for the origin and distribution of tectonic fractures in regions with multiple and heterogeneous deformation events are still considered as characterized by a high degree of uncertainty. Indeed, it is known that fracture networks development is dependent by many factors, such as composition, diagenesis, structural position, fold bending and changes in the tectonic stress history. However, several studies noted that the high-curvature regions of large folds often show a good correlation between the measured and theoretical geometry of the fracture sets. This research presents a field- and digital outcrop model-based structural investigation of refolded km-scale sheath fold (Caprazoppa mega-fold) and associated fractures host in a metamorphic carbonate sequence (Ligurian Briançonnais, Western Alps) that experienced multiple regional deformation phases. The orientation of the fracture sets along the 3D fold structure are broadly consistent with the network theoretically expected as due by the main sheath fold curvature. The subsequent, less intense ductile phase produced significant change of the structural patterns only in the schistose lithologies, whereas the more competent rocks mostly recycled the early foliations and fracture sets. Even the post-metamorphic brittle faulting/fracturing selectively reactivated the pre-existing fractures favorably oriented. We infer that, when strain is high, the strongly curved sheath folds exert a major control in the development of the fracture network, the geometry of which is preserved through the subsequent ductile/brittle deformation stages. Additionally, We highlight the importance to integrate the digital workflow with a fully comprehensive field-based characterization of the local litho-stratigraphic and structural setting to prevent misusing of the opportunity to treat large amounts of data with partially automated procedures.

Sub-magmatic to solid-state microstructures in late-collisional granitoids linked to transpressional-induced exhumation of Variscan crust in Asinara Island (NW Sardinia)

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Keywords: microstructures, late-Variscan magmatism, CARG Project.

In the framework of the geological mapping of sheet "n. 425-Asinara Island" (NW Sardinia, Italy) of the Italian National Geological Mapping Project (CARG Project), the medium- to high-grade metamorphic basement and the late- to post-collisional intrusive units (e.g., Carosi et al., 2024) were investigated.

Three late- to post-collisional Variscan intrusive units are recognized (Simonetti et al., 2024): (i) Castellaccio Unit; (ii) Punta Sabina Unit; and (iii) sheeted dyke complex. The Castellaccio Intrusive Unit consists of inequigranular granodiorite-monzogranite characterized by large K-feldspar laths, often defining a magmatic foliation. The Punta Sabina Intrusive Unit consists of peraluminous granitoid with stromatic enclaves. The sheeted dykes complex consists of peraluminous micro-leucogranite and pegmatite with a variable (decimetric to plurimetric) thickness.

These intrusive units are hosted in medium to high-grade micaschist, paragneiss, and within the migmatitic complex. Different deformation microstructures, from sub-magmatic to low-temperature sub-solidus conditions, are recognized (Pieruccioni et al., 2025) in the granitoid rocks. The main observed microstructures are represented by sub-magmatic fractures in K-feldspar, chessboard patterns in quartz, and by sub-grain rotation dynamic recrystallization in feldspar, suggesting high-temperature deformation conditions ($T > 650$ °C). Solid-state medium to high-temperature deformations ($T > 450$ °C) are provided by bulging in feldspar, myrmekites, grain boundary migration, and sub-grain rotation dynamic recrystallization in quartz. Low-temperature ($T < 450$ °C) sub-solidus microstructures consist of quartz bulging, mica kinks, and feldspar twinning and bending.

These features highlight that the three intrusive units were affected by tectonic stresses during cooling, without developing a strong penetrative meso/microstructural planar fabric, as observed in other sectors of the Variscan Orogen. The complete sequence of deformation microstructures, recorded in all intrusive units, suggests a weak but still ongoing deformation regime during granitoid emplacement in northwestern Sardinia. These observations are similar to the features highlighted in other sectors of the southern Variscan belt (e.g., Maures–Tanneron Massif, Argentera Massif, Aiguilles Rouge Massif, Peloritani Mountains; Fazio et al., 2020), suggesting a complex interplay between transpressional-induced exhumation of the middle/deep crust and magma migration and emplacement.

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Pieruccioni D. et al. (2025) - Microstructural investigation of Variscan late-collisional granitoids (Asinara Island, NW Sardinia, Italy): New insights on the relationship between regional deformation and magma emplacement. Geosciences, 15, 108, https://doi.org/10.3390/geosciences15030108.

Simonetti M. et al. (2024) - A review of criteria, methods, and standards for mapping crystalline terrains: Integrating field geology and analytical data. Ital. J. Geosci., 143, 426-454, https://doi.org/10.3301/IJG.2024.22.

New data on active tectonics at the boundary zone between the Abruzzo and Molise Apennines: the Sheet 379 Capracotta

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Keywords: active normal faults, geological-structural mapping, Abruzzi-Molise boundary zone.

The sheet 379 Capracotta is located at the transition zone between the Abruzzi autochthonous carbonate units and the Molise allochthonous nappes. Here we present a contribution focused on the geometry, kinematic and chronological characterization of the normal fault systems with evidence of activity during the Quaternary, with particular attention to those showing signs of active and capable seismogenic sources.

These normal faults, mostly already known in the literature, are located in the eastern sector of the Sheet where they constitute the "typical" normal fault in the backlimb of carbonate anticlines, a characteristic element for many active and capable seismogenic structures of the central-northern calcareous Apennines (e.g. Mt Vettore; Gran Sasso-Campo Imperatore; Mt Morrone). From north to south, they are: the Mt Porrara faults and the related Palena splay, Mt Pizzalto fault, Mt Rotella – Rivisondoli fault, Cinque Miglia - Aremogna fault. They show a NNW-SSE direction, with a main SW-dip bordering intermontane basins to their HW, often with endorheic characteristic. They are filled by continental Quaternary fluvio-lacustrine and fluvio-glacial deposits. One of the main purpose was to verify the faults continuation or not towards the SE, i.e. in correspondence with the transversal lineament Ortona-Roccamonfina (Sangro-Volturno thrust-zone Auct.). The new surface survey data, however, have not allowed us to identify places where the above-mentioned faults can clearly extend towards the southeast, thus remaining an open question as to whether this could be due to the scarcity and quality of outcrops in the predominantly clayey deposits of the Molise nappe and/or the presence of significant levels of decoupling at the base of the allochthonous sequence, or to interference phenomena with the possible transversal structural barrier represented by the Sangro-Volturno thrust-zone (similarly to what was observed for the 2016 seismic sequence between Mt Vettore and the lateral ramp of the Mts Sibillini thrust). The control exerted by inherited structures, from previous tectonic phases, have in fact been recognized, highlighting the possible reactivation and inversion of these faults during the syn- and post-orogenesis history of the Apennines. The presence of low-angle structures, like the 30°-dipping Mount Rotella fault, probably represent a case of positive inversion of a Mesozoic structure during orogenesis. In turn, there is evidence that this fault underwent a negative inversion during Quaternary.

In particular, paleoseismological investigations through the excavation of trenches were carried out on the most internal structures of the Piana della Cinque Miglia and the Piana dell'Aremogna. Here we present new data that provides information of at least 4 Holocene events (post- 5584 B.P), enabling evaluations on slip rates, recurrence time, and seismic history of the fault system.

Plio-Quaternary morphostratigraphy and paleolandscapes of the upper-middle Liri Valley (390-Frosinone sheet, CARG project)

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Keywords: paleolandscape, morphostratigraphy, landscape evolution.

The Plio-Quaternary represents a critical period of drastic tectonic and climatic changes in the Apennines, driving the landscape evolution that shaped the current surface morphologies. Temporal variations in the rate and magnitude of these processes led to differences in erosion and deposition within continental basins, resulting in a succession of distinct landscape configurations over time. The geomorphological and morphostratigraphic study of these features, commonly referred to as "paleolandscapes", provides fundamental insights into the evolution of the Earth surface. In the area of the upper-middle Liri Valley comprising the SE Section of 390-Frosinone Sheet (CARG Project), we carried out a detailed investigation of the Plio-Quaternary continental units, identifying the main preserved paleolandscapes. By combining geological field mapping, high-resolution Digital Elevation Model (DEM) analysis, sampling and U-Th datings, we identified five main paleolandscapes ranging from the Late Pliocene/Early Pleistocene to the Late Pleistocene, corresponding to the main synthems previously recognized in the surrounding areas (402-Ceccano sheet, ISPRA-Servizio Geologico d'Italia, 2011). Except for the paleosurface at the top of the late Messinian polygenic conglomerates (Conglomerati di Monte Prato, Fabbi et al., 2023), which in some places of the 390-Frosinone sheet reach the elevation of 1000-1200 m, the highest paleolandscape (P1), preserved in the eastern part of the area at an average elevation of 630 m, corresponds to the top of the Santopadre Formation (Angelucci, 1970; Carrara & Giraudi, 1995). An additional paleolandscape (P2), at around 400 m a.s.l., is carved into P1 and correlates mainly with braided plain fluvial deposits. Two additional paleolandscapes (P3 and P4), at average elevations of 260 m and 210 m, respectively, are inset into P2 and represent the top of two distinct successions, both characterized by lacustrine and calcareous tufa deposition. U-Th datings of these lacustrine deposits link them to the Lirino Lake Synthem (LRN, Centamore & Dramis, 2015). In particular, P3 is related to U-Th ages between > 600 to 400 ka (Forma Quesa Sub-synthem, LRN_1), whereas P4 correlates lacustrine deposits dated to ca. 165 ka (Pontecorvo Sub-synthem, LRN_2). The lowest paleolandscape (P5), found at approximately 150 m a.s.l. and mainly preserved in the southern part of the study area, can be relatively correlated with an Upper Pleistocene synthem marked by alluvial and fluvial deposits. In conclusion, considering the early Middle Pleistocene age for the P3 paleolandscape, we can tentatively attribute a Lower Pleistocene age to P2 and a possible Late Pliocene age to P1.

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Multi-approach study to genetically characterize dolines in the SE sector of the Classical Karst Region (NE Italy)

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Keywords: geomorphological mapping, karst, dolines.

Since October 2022, in collaboration with ISPRA (Italian Institute for Environmental Protection and Research) and the Geological Survey of the Friuli Venezia Giulia Region, activities have been underway for the development of Sheet 110-131 "Trieste-Caresana" of the Italian Geomorphological Map, within the framework of the CARG project. The area under investigation covers the Italian sector of the Classical Karst, bounded by the village of Aurisina to the northwest and the Rosandra Valley to the southeast. This region is internationally recognized for the intensity of karst processes and the richness of related landforms, and has served as a reference area for karst studies since the late 17th century. The final cartographic products of the CARG project reveal a very high density of karst landforms, as evidenced, for example, by the presence - within an area of 115 km² - of 10 km² of karren fields and "griza", more than 2,700 cave entrances and over 7,000 dolines.

Within the Classical Karst, dolines are among the most emblematic and widespread landforms, exhibiting a remarkable range of morphologies and dimensions. A key issue in their characterization - particularly in mature karst systems - is the difficulty of defining their genetic origin based on field evidence alone. Over time, dissolution processes may obscure diagnostic features that distinguish dolines formed by collapse from those resulting from solution. To address this, a range of morphometric parameters is assessed to classify dolines according to the prevailing genetic mechanism.

Remote sensing and field survey activities conducted as part of the CARG project have enabled the acquisition of extensive new data on surface karst landforms. In particular, the availability of a high-resolution (0.5 m) Digital Elevation Model has significantly improved the accuracy of morphometric analyses. All karst depressions and their bottoms were digitized. A morphometric analysis within a GIS environment was carried out to extract significant parameters and assess their applicability in determining the genetic process of individual dolines.

In order to calibrate the selection of morphometric parameters to be used, several in-depth study methodologies were applied at selected specific sites. In particular, geophysical surveys were conducted to analyze the configuration of the bedrock beneath the soil cover. ERT profiles, refraction seismics, and electromagnetic methods were employed. At the same time, a geomorphological analysis was carried out in the study area to highlight the relationship between the presence of dolines and ipogean karst features, whether active or relict.

This methodology made it possible to develop and propose a preliminary genetic model of dolines for the Classical Karst, accompanied by considerations regarding the most effective strategies for representing these landforms in geomorphological mapping.

Inheritance of pre-orogenic faults affecting Cenozoic paleogeographic evolution in the Alburni Mountains, Southern Apennines

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Keywords: Southern Apennines, Paleogene-Neogene paleogeography, CARG project.

In the framework of a "broken" foreland systems the reactivation of pre-existing tectonic structures leads to the compartmentalization of sedimentary pathways and depositional areas within the foredeep basin system and beyond. The Alburni Mountains document how the Cenozoic reworking of Late Cretaceous normal faults fragmented the Southern Apennines foreland system into depocenters characterized by differential subsidence as testified by strong closely spaced sedimentary facies variations. In this carbonate platform massif, the typical Late Cretaceous Radiolitids Limestones of the Alburni-Cervati tectonic unit (Bonardi et al., 2009) are overlain by a calcareous breccia likely representing base-of-escarpment apron deposits. Besides, the Eocene platform carbonates (i.e. Trentinara Formation) are absent, replaced by either basinal clayey siltstones with cherty limestones or outer-margin macroforam-bearing calcarenites. These laterally and vertically continuous sequences are blanketed by a polymictic breccia with a yellowish calcareous matrix and successively covered by Late Miocene siliciclastic deposits containing large crystalline, rounded pebbles and cobbles. This heterogeneous depositional environment started developing at the Cretaceous-Paleogene boundary as suggested by the escarpment deposits only containing Late Cretaceous clasts. The unconformable contact between these Late Cretaceous deposits and the Eocene basin-fill succession is straightforwardly marked by the occurrence of a diagenetic overprint of oxidized crusts and nodules, right onto the paleo-escarpment surface. These paleo-escarpments likely developed as the outcome of extensional tectonics active since the Early Paleogene, leading to the development of localized, relatively shallow- and deep-marine, fault-bounded depocenters, and were later revitalized in the Early Miocene.

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The Internal Units of the Southern Apennines Reinterpreted: Insights from the CARG Project

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Keywords: internal units, tectonostratigraphy, Southern Apennines.

The "internal units" of the Southern Apennines have long posed significant challenges in geological research due to their complex lithological variability, intense tectonic overprinting, and the lack of consistent and standardized nomenclature. These units are intensely deformed, often chaotic at the outcrop scale, and generally lack robust age constraints for viable regional correlations and tectonostratigraphic reconstructions. Moreover, the current lithostratigraphic nomenclature contains terms referring to units of well-proven external origin.

This study examines the internal "Parasicilide" units exposed in the Calore Valley (central Cilento), well exposed in the sheets 487 Roccadaspide and 488 Polla, and in minor extent also in the sheet 469 Muro Lucano. Through detailed field mapping, structural analysis, and sedimentary facies interpretation, we characterize a composite succession of terrigenous pelitic to marly-calcareous to arenaceous and chaotic shaly deposits. Field evidence and comparison with surrounding areas suggest a new and simpler tectono-stratigraphic framework that can be used for mapping the aforementioned geological sheets, aimed also at clarifying their paleogeographic significance within the broader evolution of the Southern Apennines. Our proposed lithostratigraphic nomenclature includes the Genesio Shales, the Torrente Trenico Marls / Monte Sant'Arcangelo-type deposits, the Pianelli Sandstone, and the Varicoloured Clays (Nardi et al., 2005; Sgrosso et al., 2010). The Albanella Sandstone, quoted as the upper part of the succession, corresponds to the San Mauro thrust-top deposits.

The succession bears clear evidence of deep marine, oceanic sedimentation followed by synorogenic turbiditic and mass-transport deposition; it was later involved in polyphase tectonic deformation during the Paleogene to the early Miocene (Vitale et al., 2011) and was later emplaced above the Mesozoic carbonate platform during the Burdigalian deformation stage (Patacca & Scandone, 2007).

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The first official geological map of Pantelleria Island (Sicily channel, Italy) at 1:25,000 scale: Field survey according to CARG Project guidelines

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Keywords: CARG, Pantelleria, volcanology.

In the framework of the CARG Project a detailed geological survey of the active volcanic island of Pantelleria has been performed, including not only the emerged part of the island but also the surrounding submerged areas (still in progress). Despite being subject of numerous specific volcanological and petrological studies (Mahood & Hildreth, 1986; Civetta et al., 1988; Jordan et al., 2018; Rotolo et al., 2021) the island lacked an official geologic map before the CARG project.

Here we present the results of the detailed geological survey of the onshore area of Pantelleria island performed at a scale of 1:10,000 integrated with new geochemical and geochronological data and innovative analytical techniques:

- digital acquisition of field data through the open source Qfield mobile App;
- high resolution visualization methods (Digital Elevation Model and Red Relief Image Map);
- aerial drone footage performed in inaccessible areas and along vertical cliffs;
- petrochemical analyses and 40Ar/39Ar age determinations.

The stratigraphical reconstruction of the numerous depositional units, made possible thanks to the collaboration between the Geological Survey of Italy and the University of Palermo, resulted to be very complex due to the challenging correlation between compositionally similar pyroclastic deposits and lava units erupted by the numerous clustered and overlapping eruptive centres. The application of the CARG Project guidelines, involving the use of Unconformity-Bounded Stratigraphic Units (UBSU) in addition to the lithostratigraphic criteria, highlighting the main phases of the volcanological history of Pantelleria, represented a useful tool to reconstruct the stratigraphical relationships between deposits and volcano-tectonic structures recognized.

The complex volcanological history of the island is characterized by both several episodes of volcano-tectonic collapse closely tied to ignimbrite eruptions, overlapped by asymmetric resurgence anda plethora of eruptive centers (extra- and intra-caldera), whose spatial distribution closely recalls the NW-SE trend of the Sicily Channel rift.

From a petrological perspective, rock composition varies from peralkaline rhyolites (i.e. pantellerites), by far the most abundant rock type (lava flows, pumice falls or ignimbrites) to metaluminous trachytes (lava flows, ignimbrites) to mildly alkaline basalts (scoria cones, lava flows). Impressive rheomorphism and intense welding is widespread in ignimbrites and obscure primary depositional internal architecture resulting often in difficult lateral correlations.

On the base of a critical review of the numerous studies carried out over the past years, the presented geological map with its more than sixty identified units represents a step forward as it provides a comprehensive reconstruction of the evolution of the entire island, essential basis for future studies concerning volcanic hazard assessment and geothermal exploration.

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Reassessment of the relationships between Pietraforte and Flysch della Tolfa: new data from the sheet "363" Civitavecchia of the Geological Map of Italy 1:50.000 (CARG Project)

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Keywords: External Ligurian Domain, geological mapping, stratigraphy.

The stratigraphic relationships between Pietraforte (PTF) and the Flysch della Tolfa (FYT) formations in northern Latium are object of scientific debate and conflicting interpretations, due to poor outcrop conditions. In the context of the evolution of the Ligurian accretionary wedge, these units have been interpreted as belonging to: i) two distinct units in stratigraphic continuity, part of a succession belonging to the outer Ligurian domain (Alberti et al., 1970); ii) two distinct units, one more internal and one more external, tectonically superimposed, belonging to the Ligurian domain (Fazzini et al., 1972); iii) a single unit, belonging to the Ligurian domain, with the PTF representing a lens within the FYT (Civitelli & Corda, 1982) iv) two distinct tectonic unit belonging to the outer Ligurian domain and to the sub-Ligurian domain (Bonazzi et al., 1992).Detailed geological mapping, paired with biostratigraphy and facies analysis of the Sheet 363 "Civitavecchia" at 1:50.000 of the CARG project enabled a more accurate analysis and a re-evaluation of such debated stratigraphic relationship.

Two main PTF lithofacies crop out: the pelitic, polychrome, Mn-rich Pietraforte manganesifera (PTF_a), that, due to its rheology, represents a detachment level in the chain building, and the arenaceous Pietraforte arenacea (PTF_b). The lower member of FYT (FYT_1), which is in contact with the PTF, is represented by limestone, resedimented calcarenites and marls, and by a lithofacies (FYT_{1a}) characterised by shales and sandstones. Biostratigraphic attributions are based on integrated analyses of microforaminifera, larger benthic foraminifera in resedimented calcarenites and calcareous nannofossils.

Biostratigraphic data indicate that the base of the PTF_a, Aptian-Albian in age, predates PTF_b, which begins in the latest Cenomanian. From the Cenomanian–Turonian boundary onward, the two lithofacies are heteropic. PTF_b never provided ages younger than the Coniacian, while the PTF_a yields the youngest ages (Coniacian/Santonian). The uppermost part of the PTF_a shows a gradual increase in limestones, resembling the FYT. These lithostratigraphic and biostratigraphic data suggest a stratigraphic passage that, despite poorly exposed outcrops, has also been observed in the field in the northeastern sector of the mapped area. This interpretation can be also supported by petrographic analyses on sandstones, performed in order to ascertain common provenance between the two stratigraphic units. All the analysed clastic intervals can be classified as lithoarenites thus showing a common feeding and corroborating the stratigraphic continuity between PTF and FYT_1.

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The highest-grade metamorphic basements of the Peloritani Mountains (NE Sicily): new insights from the Sheet n. 588 Villa San Giovanni

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Keywords: geological map, poly-orogenic basements, Southern Italy.

The ongoing investigations carried out as part of the new Sheet 588 "Villa San Giovanni" of the Geological Map of Italy (CARG Project) at a 1:50,000 scale area contributing to an improved understanding of the exposed crystalline basements in the area. This work is leading to a redefinition of the relationships between the high-grade metamorphic basements and several types of intrusive rocks, as well as a more accurate retracing of their mutual contacts and their relations with the sedimentary cover. Field mapping is being conducted using both traditional tools (such as compass and paper geological maps) and digital applications, including *FieldMove Clino* and *ArcGIS Field Maps*. An integrated approach, including remote sensing data such as aerial photographs and detailed digital terrain models (DTMs), is helping to address issues not directly resolvable through fieldwork alone. Field-oriented thin sections are being analyzed to gather preliminary information on microstructures and kinematics, as well as to give an estimate of the temperature evolution of the investigated basement rocks. This is with the final aim to reconstruct solid blasto-deformational relationships, contributing, in turn, to a more robust understanding of the tectono-metamorphic evolution of this sector of the Peloritani crystalline basement.

The Peloritani Mountains, in NE Sicily, are the southern termination of the Calabria-Peloritani Orogen (CPO), a poly-orogenic basement made up of remnants of Variscan and also older relic basements, nowadays incorporated into the Alpine-Apennine orogenic system. The entire Peloritani belt can be subdivided into two complexes characterized by distinct tectono-metamorphic histories (Cirrincione et al., 2015 and references therein). Within the upper complex, only the Aspromonte Unit (AU) is exposed in the surveyed sheet. The AU exhibits the most complex evolutive history of the CPO because its crystalline basement records three different orogenesis, i.e., Cadomian, Variscan and, finally, Alpine.

The dominant metamorphism recorded is Variscan, largely responsible for the main foliation recognisable in the field. The Alpine tectono-metamorphic effects consisted in the isoclinal refolding of Variscan folds and, especially, in the production of horizons of cataclastic to, locally, mylonitic rocks. The AU Variscan metamorphic basement is predominantly made up of amphibolite-facies biotite paragneisses and augen gneisses, locally intruded by late Variscan para-concordant peraluminous granites and trondhjemites, with the latter outcropping only in the southernmost sector of the surveyed area. Minor amphibolites, granitoid gneisses, mica-schists and marbles are also locally found. Both ortho- and paragneisses exhibit localised to intense migmatization, with an upward-increasing gradient. The migmatization processes are characterized by phlebitic, stromatic and nebulitic structures, with most of the rocks occurring as metatexites, and, locally, diatexites.

Cirrincione R. et al. (2015) - The Calabria-Peloritani Orogen, a composite terrane in Central Mediterranean; its overall architecture and geodynamic significance for a pre-Alpine scenario around the Tethyan basin. Per. Min., 84, 701-749.

An integrated Geological-Geophysical approach for recognizing the major tectono-stratigraphic units of the 350 - Penne Sheet (CARG Project)

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Keywords: Mio-Pliocene foreland basin system, sub-surface geology, first tectonic-stratigraphic setting.

The relaunch of the CARG Project has created new opportunities and challenges. One of the main objectives in the ongoing 350–Penne Sheet is to enhance our understanding of the tectono-stratigraphic evolution of the Mio-Pliocene Foreland Basin System in the Abruzzo Apennines. A key strategy to tackle this challenge involves detecting the primary tectono-stratigraphic units into which the basin has been divided during the Plio-Quaternary thrusting.

To achieve this goal, we performed a 1:10.000 scale fieldwork in a key area located in the central portion of the Sheet. The survey aimed to assess the southward continuity of the successions of the Laga and Cellino Fms., described and mapped in the adjacent 339-Teramo Sheet. This preliminary investigation highlighted both analogies and differences, and led to the identification of new potential lithostratigraphic units, such as formations, facies associations and key-horizons. The geological map obtained reveals the internal structure of the major thrust sheets, although the precise locations of some thrust traces remain uncertain, due to the poor exposures.

The turbiditic origin and compositional similarity of both Laga and Cellino Fms., make it challenging their distinction if based only on the lithostratigraphic criteria. It is important to note that, in this preliminary phase of the project, results from biostratigraphic and petrographic analyses are not yet available. We then attempted to differentiate the major thrust faults from the minor splays by integrating field data with subsurface investigation.

In this context, the interpretation of publicly available seismic lines from the Vi.D.E.P.I. Project was a crucial resource. After calibrating the seismic data with three exploitation wells and integrating it with surface geological information, we gained insights that helped to pinpoint the likely location of the surface thrusts and proposed an initial subdivision of tectono-stratigraphic units.

Although a complete subsurface model is not explicitly expected for the 350 Sheet, our work demonstrates how seismic interpretation can contribute to: i) identify the connections between buried structures and outcropping ones; (ii) highlight regional-scale master faults considering the associated amount of slip; and, (iii) support the surface interpretation of the main stratigraphic tops, especially where they display a clear seismostratigraphic evidence.

CARG Sheet Empoli 274: between new Insights, unresolved issues, and broader reflections

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Keywords: geological cartography, Neogene, Tuscany.

The geological survey of the CARG Sheet 274 "Empoli" at a 1:50,000 scale provided a valuable opportunity to update the geological understanding of a key area in central Tuscany through the application of a multidisciplinary approach. This region, renowned for its rich fossil deposits that once captivated Leonardo da Vinci, continues to serve as a natural laboratory where sedimentary, paleoenvironmental, and tectonic dynamics interact in complex ways, directly influencing cartographic representation. The exposed deposits are predominantly Pliocene in age, specifically Piacenzian, and consist of marine, transitional, and continental successions. Along the eastern margin, portions of the Ligurian substrate (Sillano Formation) and the Tuscan substrate (Macigno, Monte Modino Unit, Falda Toscana) are also exposed. The Neogene-Quaternary depositional facies are characterized by shallow marine environments, which transition laterally into deltaic, lagoonal, and fluvial settings. These units are organized into numerous high-frequency transgressive-regressive (T-R) sequences (sensu Embry & Johannessen, 1993), marked by frequent discontinuity surfaces. However, documenting these cycles remains challenging due to insufficient biostratigraphic and chronostratigraphic resolution, primarily resulting from the limited quality of outcrops. Tectonically, the area forms part of the extensional basin systems that developed in response to the opening of the Tyrrhenian Sea (from the late Tortonian) and the concurrent counterclockwise migration of the foreland mountain system (Malinverno & Ryan, 1986; Patacca et al., 1990). Recent studies, however, have emphasized the potential role of compressive tectonics in the development and evolution of these basins (Buttinelli et al., 2024, and references therein), and the debate on this topic remains open. From an operational perspective, ensuring interpretive consistency with adjacent geological sheets led to the organization of the cartographic division using a combination of lithostratigraphic units and members. This approach was derived from the previous subdivision into synthems and sub-synthems. Harmonizing these units required a revision of the original legend, shifting from a lithological to a stratigraphic-interpretive format. While necessary, this revision introduced several challenges: lithologically similar members may belong to different synthems, and a single synthem may contain members with differing lithological characteristics. Despite these challenges, the multidisciplinary approach has provided valuable insights, contributing to the redefinition of the area's evolutionary framework. Strontium isotope dating has provided evidence suggesting that some deposits previously attributed to the Pliocene may instead belong to the Pleistocene. This reinterpretation carries potential implications for tectonic and depositional models, as well as for cartographic revisions. The experience gained from developing the "Empoli" sheet represents a significant advancement in geological knowledge of the region, although many issues remain unresolved. It also reaffirms the strategic importance of the CARG Project and its vision: to produce high-quality, consistent geological data for the entire country, which is essential for environmental, urban, and infrastructural planning. These data represent not only a scientific and technical resource but also a valuable cultural and public asset. However, the project also highlighted some operational limitations that should be addressed by strengthening collaboration among universities, research institutions, and ISPRA.

Geological and petrographic aspects of Monte Arci volcanic complex (central Sardinia, Italy)

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Keywords: rhyolites, anorogenic magmatism, transtensive faults.

The Plio-Pleistocene volcanism of Sardinia (Italy) represents a good example of intraplate (anorogenic) magmatism which is, schematically, made up of plateaux of broadly basaltic composition and locally central composite complexes in which occurs contrasting fingerprint documented by Basanite/Phonolite sequence (Monte Ferru) and rhyolite magmas (Monte Arci).

Monte Arci volcanic complex (about 100 km^2; Central Sardinia) outcrops at the edge of Campidano though, along NNW trending transtensional faults which channelized magmas at upper crustal levels. This complex is made up of a lower sequence (dated at 3.6 ÷ 3.2 Ma) 300 m thick dominated by metaluminous to peraluminous rhyolites and subordinately trachytes and latites. The lower sequence is covered by a thin sequence of basaltic lava flows showing subalkaline to middle alkaline affinity (2.65 Ma). Remarkably, disequilibrium textures are commonly observed in all the volcanic episodes and are mainly documented by sieve textures in plagioclase feldspar and by corrosion of both mafic and sialic phases, probably in response of vertical development of magma reservoirs. In addition, quartz xenocrysts with continuous reaction rims of Cpx are observed in basaltic lava flows of alkaline affinity, possibly documenting assimilation processes. Rhyolites main association is Qz + Kfs + Fe-Bt + Na-Pl; K-feldspar of centimetric size represents the main phase of trachytes. Latites are characterized by Opx + Cpx + Pl while basaltic rocks of the upper sequence are mainly formed by Ol + Cpx + Opx.

Several lines of evidence, confirmed by published Sr-Nd isotopic systematic, support a petrogenetic model requiring crystal/liquid fractionation and assimilation of latite magma. This intrusion triggered the partial melting of upper crustal levels, leading to rhyolitic magmas segregated at the top of mafic reservoirs.

The switch to dominantly basaltic magmatism at the end of Pliocene, could reflect either an abrupt change in tectonic setting or, according to the general lack of primitive basaltic magmas, the expected incubation time required by basaltic underplates.

The Pliocene Tolfa dome complex, an early volcanic event in the recent geodynamic evolution of the Italian peninsula: insights from new field, geochronological, geochemical, and petrologic data

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Keywords: Tolfa dome complex, geological mapping, geochronology.

The Tolfa dome complex documents a Pliocene volcanic event that occurred during the geodynamic evolution of the Central Mediterranean, in the hinterland of the eastward migrating Appenine orogen. The Tolfa dome complex belongs to a widespread high-silica volcanism in Northern Latium that borders the Tyrrhenian shoreline, north of Rome, and predates the leucite-bearing volcanism of the Roman Province of a few million years. New field, morphometric, geochronological, geochemical, and petrologic data were collected in the context of the new geological mapping for the compilation of the Sheet #363 – Civitavecchia (1:50,000 scale), included in the CARG national project, which allowed to refine our understanding of the Tolfa volcanism in the framework of the Apennine-Tyrrhenian geodynamics. The present study was performed through a multidisciplinary approach, which integrated a detailed geological mapping, biostratigraphy, geomorphology, geochemistry, volcanology, geochronology and petrography.

The Tolfa dome complex is made up by lava flows, coulees, and coalescing exogenous domes, covering an area of about 30 km^2. Feeder dikes and sills are also found in the periphery of the complex, especially in the northwest sector (Cencelle site). Silicic lava flows, associated with the exogenous domes, are also found in the southern sector at the Tolficciola and Tolfaccia sites. Volcanism occurred at the transition from shallow marine to sub-aerial environments, as attested by occurrence of peperites, suggesting interaction between magma and water-saturated, unconsolidated soft marine sediments. The volume of the emplaced magma was estimated to be about 2.4 km^3. The emplacement of the domes led to a regional-scale uplift, as evidenced by the upwards transition from bathyal facies of the *argille azzurre* (Zanclean) to shallow-water facies of the *macco* calcarenites (lowermost Piacenzian). Detailed biostratigraphic analysis provides constraints to estimate the rate of this uplift.

High-precision $^{40}Ar/^{39}Ar$ dating indicates a relatively short time span for the emplacement of domes and lavas, as short as 43 ± 10 ka (from about 3.48 to 3.43 Ma). These ages are slightly younger than those of the Ceriti dome Complex but significantly (up to about 1.4 Ma) older than the Manziana volcanic center, both representing two neighbouring volcanic events belonging to the same magmatic epoch. The volcanic rocks range in compositions from trachyte/trachydacites to subordinate rhyolites. They have SiO_2 from 64.3 to 72.1 wt.%, MgO from 0.16 to 1.46 wt.%, K_2O from 4.93 to 9.89 wt.%, Rb from 297-482 ppm, Sr from 147 to 582 ppm, La from 49.5 to 133 ppm, and Th from 26.6 to 35.0 ppm. Results are consistent with a genesis of magmas through mixing between magmas derived by partial melting of the continental crusts and mantle derived magmas.

The medium- to high-grade metamorphic basements of NW Sardinia: the example of the Sheet n. 425 “Isola Asinara”

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Keywords: geological mapping, Variscan basement, CARG project.

In the Asinara Island (NW Sardinia) it is possible to investigate the medium- to high-grade metamorphic basement which formed the inner part of the Variscan orogen as well as a km-scale transpressive shear zone, *i.e.* the Posada-Asinara shear zone, that drove the exhumation of the metamorphic core of the belt (Carosi & Oggiano, 2002). Because of the former limitation of access that lasted for many years, only recently a structural-geological maps of the island was made (Carosi et al., 2024).

The island falls in the area covered by the geological sheet “424 - Isola Asinara” of the CARG project. The sheet, currently under production, is realized following the modern approach and standards to map crystalline basements suggested by the new project normative (Simonetti et al., 2022, 2024) provided by the Italian Geological Survey. This basement is characterized by two tectono-metamorphic units (TMU): the Internal Zone made by rocks of the High Grade Metamorphic Compelx and the *Zona a Falde* made by rocks of both the the High Grade and Medium Grade Metamorphic Compelxes; and three intrusive units: the Castellaccio intrusive unit, the Punta Sabina intrusive unit and sheeted dykes intrusive unit.

The Medium-Grade Metamorphic Complex consists of i) albite/oligoclase bearing micaschist; ii) garnet and staurolite bearing micaschist; iii) quartzite; iv) amphibolite; v) Cala Reale orthogneiss; vi) Cala d’Oliva ortogneiss; vii) sillimanite bearing micaschist; viii) mylonitic sillimanite bearing micaschist.

The High-Grade Metamorphic Complex consists in i) migmatite; ii) migmatitic amphibolite; iii) Punta Scorno orthogneiss.

The two TMU are separated by the Posada-Asinara Shear Zone that, in agreement with the new normative of the CARG project, was mapped taking into account the occurrence of both sillimanite and evidences of non-coaxial deformation.

The Castellaccio intrusive unit consists of inequigranular granodiorite-monzogranite characterised by large laths of K-feldspar, which often define a magmatic foliation. The Punta Sabina intrusive unit consists of peraluminous granitoid with stromatic enclaves, and finally, the sheeted dykes intrusive unit consists of peraluminous micro-leucogranite and pegmatite from decimetric to plurimetric thickness.

Carosi R. & Oggiano G. (2002) - Transpressional deformation in northwestern Sardinia (Italy): Insights on the tectonic evolution of the Variscan belt. C. R. Geosci., 334(4), 287-294,

Carosi R. et al. (2024) - Geology of the Asinara Island (Sardinia, Italy). J. Maps, 20(1), 2317136.

Simonetti M. et al. (2022) - Indicazioni per il rilevamento e la rappresentazione del basamento cristallino, in Quaderni del Servizio Geologico d’Italia, serie III, 15, 83-98.

Simonetti M. et al. (2024) - A review of criteria, methods, and standards for mapping crystalline terrains: Integrating field geology and analytical data. Ital. J. Geosci., 143, 426-454.

Advances in geological mapping of the Western Ligurian Alps: structural and stratigraphic reinterpretation from the CARG sheets Ormea and Albenga (n° 244 and 245)

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Keywords: mapping, Western Ligurian Flysch, Alps.

The Western Ligurian Flysch, a key tectonostratigraphic domain in the Alpine belt, is here redefined for the areas of Ormea (n°244) and Albenga (n°245) sheets in the frame of the CARG new geological mapping. These updated surveys significantly enhance previous geological interpretations by distinguishing lithostratigraphic units that were once considered undifferentiated and by refining lithological boundaries, thrust faults, and shear zones.

The western Ligurian Alps preserve a complete stratigraphic record of both European and oceanic domains, including the Piedmont–Ligurian, Briançonnais, and Dauphinois units and offering a natural laboratory for studying the Alpine orogenic evolution. In literature, the ligurian "*Helminthoid Flysch*" nappes are interpreted as originally deposited as deep-sea turbidites in the closing Alpine Tethys Ocean. Then they were detached from the Piedmont–Ligurian subduction trench during the Alpine orogeny and emplaced onto the foreland, forming the uppermost tectonic units of the orogenic wedge.

Our new mapping data, integrated with structural and sedimentological analyses, provide a more detailed and accurate model of nappe stacking, tectonic transport, and syn-orogenic sedimentation for the studied area. This improved geological framework catches the complex interplay of accretionary prism dynamics, crustal shortening, and foreland propagation, reaffirming the Western Ligurian Flysch as a critical area for deciphering the Alpine geodynamic evolution.

This study builds on the fundamental and pioneering study of Boni & Vanossi (1972) whose 1:100,000-scale geological map ("*Carta geologica dei terreni compresi tra il Brianzonese ligure s.l. ed il Flysch ad Elmintoidi s.s.*") laid the groundwork for understanding the regional structure and stratigraphy. The new detailed geological mapping, including recent data and modern methodologies, allows to propose and advanced picture of the architecture of the Western Ligurian Flysch, enhancing its role in regional tectonic and stratigraphic research.

Boni A. & Vanossi M. (1972) - Carta Geologica dei terreni compresi tra il Brianzonese ligure s.l. ed il Flysch a Elmintoidi s.s. Atti Ist. Geol. Univ. Pavia.

Geological mapping in highly anthropized areas: the multitasking approach experienced for the Sheet 363 Civitavecchia 1:50,000 (CARG Project)

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Keywords: geological mapping, urban geology, Civitavecchia.

Urban and highly anthropized areas represent a significant challenge for geological mapping, due to a range of methodological and practical issues. Human activity, through infrastructure, industrial development, and agriculture, has profoundly altered the natural landscape, often limiting access to outcrops and preventing the use of traditional field-based mapping methods. In such contexts, adopting alternative and integrated strategies becomes essential.

Accurate geological mapping in urban areas is not only important for scientific purposes, but also for land-use planning, hazard mitigation, groundwater management, and infrastructure development. This creates a paradox: where mapping is most difficult or even impossible, it is often most urgently needed.

In areas where urbanisation has modified or completely erased natural geological evidence, an integrated approach is required. This combines limited direct field data with indirect sources: analysis of historical maps, aerial photos, and documentation, as well as geognostic data from human activities such as excavations, geotechnical boreholes, and well logs.

The Sheet 363 Civitavecchia (Geological Map of Italy, 1:50,000 scale, CARG Project) covers a territory with a long history of human activity and landscape transformation, dating back to the Etruscan and Roman periods. Major challenges were encountered in urban areas, lowlands along the Tyrrhenian coast, and in port, industrial, and agricultural zones, where natural outcrops are scarce or absent. The adopted methodology included a thorough review of scientific literature, historical sources, and geognostic data. Valuable support came from the Italian Database of Shallow Boreholes and Digital Elevation Models, aiding in the reconstruction of the geological setting despite the urban constraints. Additional data were obtained from accessible quarries, canals, and watercourses within the urbanised area, as well as the coastal zone, which, although heavily modified, still preserves some outcrops. In recently urbanised sectors, such as the port of Civitavecchia, previous studies (e.g., Fazzini et al., 1972) and photographs of outcrops proved crucial to reconstructing now-lost exposures.

Outside urban areas, another difficulty arises from the renaturalisation of anthropic features, such as canals or embankments, which may mimic natural landforms like fluvial or marine terraces, making them difficult to identify. Moreover, in zones where agriculture has reshaped the soil profile for over two millennia, surface evidence is often unreliable for interpreting the shallow subsurface geology.

This experience underscores the importance of adaptive methodologies in geological mapping activity aligned with CARG Project standards under anthropized conditions.

Fazzini P. et al. (1972) - Geologia dei monti della Tolfa (Lazio settentrionale; province di Viterbo e Roma). Mem. Soc. Geol. It., 11, 65-144.

Sheet 212 “Spigno Monferrato”of the Geological Map of Italy at 1:50.000 scale (CARG Project): preliminary results of geomorphological mapping

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Keywords: CARG, geomorphological mapping, landslides.

This study, aiming at surveying and mapping the geomorphological elements for the CARG Sheet no. 212 “Spigno M.to”, started in 2024, within the ISPRA CARG project for the drafting of the Geological Map of Italy at scale 1:50.000.

The study area, in NW-Italy, comprises both Ligurian and Piedmontese territories, featured by a complex geodynamic evolution and different geological characteristics.

From a geological point of view, the area included in the ‘Spigno Monferrato’ Sheet falls within the Ligurian Alps. In this sector, the Alpine chain consists of a complex pile of tectonic units, whose lithostratigraphic and structural characteristics reflect their genesis. The tectonometamorphic orogenic system is discordantly covered by the deposits of the Piedmont Tertiary Basin, a late Eocene-Oligocene sedimentary succession.

The 212 quadrangle, mainly developed in the Po Valley basins, includes the Tyrrhenian-Po Plain watershed that runs at a short distance from the Ligurian coastline (7-12 km) and separates two slopes with significant geological and geomorphological diversity, where the relief energy plays a crucial role triggering geomorphological instability.

The surveys show a predominance of complex, roto-translative landslides, which have extremely variable landforms and are controlled not only by the steepness but also by the position on the slope and the hydrographic network.

The main landslides are often the result of a coalescence of different gravitational phenomena, which contribute to the movement of larger areas, mainly observed in the Ligurian sector of the Po Valley basin.

In the process of updating and digitizing the Geological Map at a scale of 1: 50,000 according to the new ISPRA guidelines, the first step of restitution and analysis is presented, with a specific focus on the representation and classification of landslide phenomena. Currently, the survey of the entire Ligurian territory and 20% of the Piedmontese territory is completed.

The geomorphological survey at a scale of 1:10,000 was conducted using remote sensing techniques supported by field investigations, cross-referencing newly acquired data with previous dataset information by Liguria Region, Piedmont Region, Basin master plan and IFFI project.

During data digitization, in some cases the extent and boundaries of the landslides were modified, adapting them for the representation at 1:25.000 and 1:50:000 scale, coding them according to the representation and archiving standards required by the Istituto Superiore per la Protezione e la Ricerca Ambientale (I.S.P.R.A.).

The Lessini Mountains, central Southern Alps: New structural and stratigraphic constraints on their evolution from the mapping of sheet 124 "Verona Est" (CARG project)

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Keywords: Eocene Southern Alps tectonics, Castelvero Fault, syn-tectonic volcanism.

New structural and stratigraphic data from the Lessini Mountains are becoming available in the framework of the geological mapping activities for the 1:50,000 Verona Est sheet (CARG project). The Lessini Mts. form the southernmost exposed termination of the Eastern Southern Alps, before the bedrock disappears to the south beneath the Pleistocene sedimentary cover of the Pianura Veneta. We are currently mapping and studying a ~1 km thick Upper Triassic to Upper Cretaceous carbonate multilayer succession that experienced pervasive dolomitization during the Eocene. This metasomatism was of hydrothermal origin and likely associated with Eocene extensional tectonics during extensive volcanic activity of the Venetian Volcanic Province. Eocene extension was largely accommodated by the regional ENE-dipping Castelvero normal fault (CF), bounding to the west the NW-SE trending Alpone graben. The CF footwall contains part of the Adria-related Jurassic to Cretaceous carbonate succession, whereas the hanging wall is generally formed by the Eocene volcanic sequence and syn-volcanism platform carbonates of the nummulitic unit.

Most of the Triassic to Jurassic succession is thoroughly overprinted by secondary dolomite, which almost completely obliterated the primary stratigraphic features, sparing only scattered remnants of Lower Jurassic units. The overprint progressively decreases upward in the Lower to Upper Cretaceous Maiolica and scaglia variegata alpina Fms, where dolomitization selectively and preferentially localised along inherited stratigraphic features (e.g., bedding and burial stylolites) and tectonic structures (e.g., high-angle fractures). The dolomitization overprint increases towards the east, i.e. towards the CF and the Lessini Mountains volcanic district, suggesting an intimate genetic relationship with Eocene deformation and volcanism.

Structural analysis of the Castelvero Fault indicates a complex fault structure, made of several NNE-SSE fault strands. Portions of the Upper Cretaceous units in the footwall of the CF, where deformation is strongly localised, form variably thick tectonic slices aligned and segmented along the strike of the main fault. Locally, they contain thick fault-rock domains with cataclasite and foliated gouge. The fault zone at times contains foliated and transposed portions of the Eocene nummulitic carbonates, which suggests post-Lutetian faulting. Volcanic products in the hanging wall are generally slightly deformed along the fault and accommodated deformation through more spaced and lower-scale faults in the whole hanging wall, where deformation is strongly partitioned.

Our ongoing field analysis points to an intimate genetic relationship between regional tectonics, stratigraphy and dolomitisation, whereby syn-tectonic and syn-volcanism dolomitisation, as well as deformation localisation where governed and guided by the local stratigraphic setting during and after the Eocene.

Burial stylolites as preferential pathways for Mg-rich fluid ingress and flow: New petrophysical/genetical constraints from hydrothermal secondary dolomitization in the central Southern Alps (Lessini Mountains – 1:50,000 Verona Est sheet, CARG project)

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Keywords: burial stylolites, dolomitization, Southern Alps.

Rock petrophysical properties such as porosity and permeability are key in controlling fluid ingress and fluid-rock interaction across scales and tectonic regimes. i) Rock density, ii) viscosity, iii) porosity and iv) permeability can, in turn, be dynamically modified by fluids as they interact with the host rock. It is thus crucial to investigate preferential fluid flow pathways, even in normally little permeable and porous rocks. In non-fractured, horizontally bedded micritic carbonates, vertical fluid flow is inhibited, whereas lateral flow is favoured along continuous planar anisotropies (e.g., bedding). Also, secondary features (e.g., burial stylolites) generally hamper vertical fluid flow, even though recent studies suggest they may also serve as preferential pathways for karst-related dissolution.

Based on an ongoing mapping effort as part of the CARG project for the Verona Est 1:50,000 sheet (central Southern Alps), we present new data on secondary dolomitisation in little permeable carbonates. We studied the petrophysical properties of the Maiolica Fm Cretaceous micritic limestone from the Lessini Mountains, where the Adria-related Mesozoic succession underwent pervasive dolomitisation during Eocene extensional tectonics and volcanic activity of the Venetian Volcanic Province. Petrographic analysis, mercury intrusion porosimetry, and helium pycnometry were used to assess the modes of ingress and flow of Mg-rich fluids and their effect on the Maiolica Fm.

Results indicate that burial stylolites in the little-porous and permeable limestone are selectively dolomitised, forming 1–10 mm thick dolomite seams, suggesting dominant bedding-parallel fluid flow. Stylolites, compared to the micritic Maiolica Fm, have remarkably lower capillary threshold pressure (3 PSI vs. 5100 PSI) and larger average pore size (65 μm vs. 0.012 μm), whereas porosity is low for both stylolites and host-rock (1 % and 3 %, respectively). Dolomitisation also occurred along vertical fractures and fracture networks, pointing to across-bedding Mg-rich fluid migration associated with normal faulting.

Progressive dolomitisation, afforded by fluid ingress along stylolites, increased rock density from ~2.65 g/cm³ in the pristine limestone to ~2.9 g/cm³ in fully dolomitised rocks. Similarly, he median value of pore size increases from ~0.012 to ~0.33 μm, porosity from ~3.2% to 21.8%, and capillary threshold pressure decreases from ~5140 to ~35 PSI. These results demonstrate that, under specific conditions, stylolites can serve as effective pathways for fluid ingress/migration, also promoting fluid-rock interaction in rocks otherwise characterised by overall low porosity and permeability. Lastly, our data show that dolomitisation can significantly modify the primary petrophysical rock properties, favouring fluid ingress and promoting fracturing and brecciation by changing the local rheology by further modulating deformation localisation/partitioning during tectonic activity.

S14.

Mountains in motion: decoding the Alpine-Himalayan orogen

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Coesite inclusions in the Voltri eclogites: another ultra high-pressure ophiolite unit in the Alps

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Keywords: coesite, Raman spectroscopy, Voltri Massif.

The findings of coesite in the Alpine, eclogite-facies, continental and oceanic lithosphere (Chopin, 1984) raised a fundamental question: how can the subducted slabs crust be exhumed from depths exceeding 90 km? Initially, the limited occurrence of UHP minerals led some authors to propose that tectonic stresses played a key role in their formation (e.g. Schmalholz et al., 2014). However, recent discoveries of coesite-bearing rocks in several meta-ophiolite units of the Western Alps (e.g. Ghignone et al., 2023) suggest that attainment of UHP conditions during Alpine subduction has been more widespread than previously thought.

Here we document for the first time the presence of coesite inclusions in garnet of the well-known eclogites of the ophiolitic Voltri Massif (Liguria). Identified through μ-Raman spectroscopy, coesite occurs either as pristine, quartz-free crystals or as partially replaced by quartz. Coesite inclusions are mostly located in the cores and mantles of zoned, eclogitic garnet porphyroblasts. Associated phases include omphacite, amphibole, rutile, and quartz, the latter often occurring near fractures and likely representing retrograde products of former coesite. The minimum pressure for coesite stability in these rocks is ~2.8 GPa at 500 °C - higher than previous estimates (2–2.5 GPa, 450 to 500 °C; Starr et al., 2020) - indicating the presence of a previously unrecognized UHP unit in the Western Alps. Ongoing thermodynamic modelling and elastic thermobarometry aim to further constrain the petrological and rheological evolution of this relatively cold UHP unit.

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Ghignone S. et al. (2023) - A new UHP unit in the Western Alps: First occurrence of coesite from the Monviso Massif (Italy). American Mineralogist, 108(7), 1368-1375.

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Mesozoic palaeogeography of Adria and the thrust front along the southern Dinarides and Albanides

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Keywords: Dinarides, Albanides, Mesozoic palaeogeography.

Adria is a N-S-elongated continental domain which is fringed on three sides by Alpine s.l. fold-and-thrust belts (FTBs). Basinal and shallow water carbonate sediments characterize the Mesozoic successions of Adria, which represents the only, almost undeformed remnant of the southern Tethyan continental margin. At the orogenic scale the Dinaride and Hellenide FTBs (E side of Adria), show a remarkable along-strike transition from continental collision to oceanic subduction. Although the deformation of the Outer Dinarides has been completed in the early Miocene, the E-W-trending southern portion of this FTB presents seismicity and evidence of active tectonics. This segment of the Outer Dinarides and its continuation into the Albanides has been investigated using a data set composed of proprietary and commercial marine multichannel seismic profiles. In the Southern Adriatic Sea the undeformed sector of the Mesozoic Dalmatian carbonate platform faces the Mesozoic Ionian basinal domain. The platform shows a finger-like shape and terminates W-ward, with the E-W inner margin that controls the structural style of the southern Dinarides thrust front. The Dalmatian carbonate platform domain continues farther south into Montenegro and in the Kruja carbonate platform of Albania, a unit completely eradicated and incorporated into the Albanide FTB (Roure et al., 2004). Eradicated carbonate formations belonging to the Dalmatian platform crop out in southern Montenegro (Ulcinj region), where they rest on basinal Oligocene sediments of the Ionian basin (Bega et al., 2015), showing a structural continuity with the Kruja platform units. A thick depocenter of Cenozoic clastic foreland sediments is present over the Mesozoic Ionian basin, which acted as a sediment sink. These sediments are currently accreted in the outer Albanides, with large-scale backthrusts that define a wide triangle zone (Roure et al., 2004; Argnani, 2013). Offshore seismic reflection data allow to infer that the triangle zone imaged in the Albanides can extend into Montenegro, defining a continuous belt of active deformation which correlates well with the largest thrust earthquakes in this sector of the FTB. The Kruja units underwent a large Neogene vertical-axis clockwise rotation (e.g., Handy et al., 2019) which is also reflected in the north-south trend of the Albanian frontal structures. The large scale rotation affected the units overthrusting the Mesozoic palaeogeographic domain of the Ionian basin, suggesting that at the scale of a few 100s km the palaeogeography of the underthrusted plate can affect the style of accretion of the FTB. This medium-scale palaeogeographic control adds to the first order, large-scale control given by the transition between the continental collision recorded in the Dinarides and western Hellenides and the oceanic subduction occurring south of Cephalonia.

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The fate of the lower crust during continental subduction in the Western Alps

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Keywords: Western Alps, lower crust, continental subduction.

The Western Alps results from a long history involving subduction of the Piemonte-Liguria Ocean, continental subduction and collision. At crustal scale, the Palaeozoic basement of the European and Adriatic palaeomargins (and intervening continental ribbons) constitutes the bulk of the material in the thickened crust (the Mesozoic covers only account for a very small amount of material). During continental subduction, this material was transformed at UHP conditions, then detached from the downgoing slab and finally stacked

Field, structural and petrological studies reveal not only the details of the Alpine history (e.g. the P-T paths of the subducted material), but also allows to characterize the pre-Alpine history. An unexpected result from these studies is that most of the material involved in continental subduction and now exposed at the surface belongs to the upper crust, not to the lower crust. To explain this paradox, we will examine how several processes may contribute to this net effect. Such processes include:

- the building of the lower crust during the pre-Alpine history, in most cases during the Carboniferous Variscan orogeny;
- the role of the Permian asthenospheric upwelling in reshaping the petrological and mechanical characteristics of the lower crust;
- its reworking during the extensional, Jurassic, construction of the palaeomargins (with the potential role of a decoupling between the lower and upper crust);
- its subduction and exhumation during the Alpine orogeny.

The importance of the structural inheritance is a key element for understanding why the lower crust remains at depth in the present thickened crust, while the upper crust was subducted then exhumed, and decoupled during a multistage history from its corresponding lower crust.

This communication will be done in recognition of the receipt of the Capellini Medal.

Shear zone affecting high-pressure metamorphic rocks in the inner Northern Apennines during exhumation (Middle Tuscan Ridge, southern Tuscany, Italy)

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Keywords: HP-metamorphism, exhumation of metamorphic rocks, Northern Apennines.

Structural and petrographic investigations were carried out on a meter-thick shear zone that deformed high-pressure quartz–carpholite–pyrophyllite–white mica metamorphic rocks exposed in the Middle Tuscan Ridge (inner Northern Apennines, Italy). This shear zone records a metamorphic evolution characterized by progressive exhumation following the metamorphic peak. The dominant fabric within the zone is marked by a main foliation, along which centimetre- to millimetre-thick boudins—locally preserving the high-pressure metamorphic assemblage—are observed.

At the microscale, these boudins are bounded by a retrogressive foliation composed of second-generation white mica, chloritoid, and chlorite. Microtextural observations also reveal post-tectonic growth of chloritoid in a characteristic "rosetta" morphology, along with static recrystallization of quartz.

Fluid inclusion analyses were carried out on quartz veins developed within the shear zone. Most inclusions are two-phase (liquid + vapour) and occur along trails, suggesting a secondary or pseudo-secondary origin. The results indicate fluids of metamorphic origin, with relatively low salinity (up to 6.0 wt.% NaCl equivalent) and formation temperatures around 350 °C.

Paleogeography, diachronous subduction-to-delamination transition and the episodic slab rollback in the Apennines

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Keywords: subduction, delamination, Apennines slab retreat.

The subduction of the Apennines in the central Mediterranean, from the late Eocene/Oligocene to the present, is marked by alternating phases of slow and fast slab rollback, orogenic wedge advancement, and backarc basin opening. The stepwise retreat of the Apennines subduction zone, along with the large-scale thinning of the overriding lithosphere, has been attributed to several possible mechanisms. These include interactions between the slab and the 660 km mantle discontinuity, the effects of continental collision and slab detachment, the subduction of thick carbonate platforms, variations in the strength ratio between transform faults and the overriding plate, a reduction in slab width, and plate damage caused by bending.

The shift from oceanic to continental subduction—and eventually to delamination—is believed to significantly influence orogenic dynamics, magmatism, metamorphism, and sedimentation-tectonic styles. Our findings suggest that the asynchronous transition from continental subduction to lithospheric delamination has been a key factor in driving the alternating phases of orogenic wedge advance and backarc extension in the Apennines. The diachronicity was controlled by different paleogeographies in the Northern and Central-Southern Apennines. By jointly analyzing the timing and rates of forebulge migration, thrusting, and backarc extension—as well as seismic anomalies within the slab—we reveal a close coupling between slab dynamics and orogenic evolution.

Tomographic profiles across the Apennines show low shear-wave velocity anomalies along the slab dip, interpreted as signs of slab damage. These anomalies are linked to the diachronous underthrusting of thick continental lithosphere in both the Northern and Central-Southern Apennines. This process likely led to the thermal weakening of the subducting crust, promoting the transition from continental subduction to delamination of the Adria plate. We propose that this diachronous transition—occurring around 21 million years ago in the Northern Apennines and about 9 million years ago in the Central-Southern Apennines—was influenced by inherited paleogeographic conditions and slab damage. This mechanism played a pivotal role in shaping the episodic nature of slab rollback and backarc extension in the region.

Normal shearing in the North Himalayan Gneiss Domes (SE Tibet): a progressive shift from the Cuonadong to the Yalaxiangbo domes

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Keywords: South Tibetan Detachment, North Himalaya Gneiss Domes, petrochronology.

The Cuonadong and the Yalaxiangbo gneiss domes are two North Himalayan Gneiss Domes (NHGD), in eastern Himalaya. They show similar tectonic units separated by an upper ductile/brittle and a lower ductile detachment, with a top-to-the NE sense of shear, linked to the dvelopment of the South Tibetan Detachment System. The sense of shear is the same on the southern and northern limbs of the domes. The upper tectonic unit, above the upper ductile/brittle detachment, includes unmetamorphosed to low-grade metamorphic Triassic-Lower Cretaceous slate and metapsammite of the Tethyan Himalayan Sequence. The middle tectonic unit, sandwiched between the upper and lower detachments, consists of mylonitic granite, staurolite-garnet-two mica schist and biotite-plagioclase gneiss affected by the ductile top-to-the north extensional shear of the lower detachment. The lower tectonic unit consists of mylonitic gneiss, leucogranite plutons, dikes, and sills. By (LASS-ICP-MS) in situ U-(Th)-Pb monazite petrochronology from sheared samples, we constrained the activity of the lower detachment at ca. 19-18 Ma and the shearing along the upper detachment later than ca. 16-15 Ma (Chen et al., 2018) in the Yalaxiangbo dome. The detachment system is made up by two different shear zones activated in different times and at different structural levels. Our data testify a migration of the deformation from the lower portions to the upper ones (Cottle et al. 2015; Kellett & Grujic 2012, Iaccarino et al. 2017, Chen et al. 2018). The ages of shearing of the ductile shear zones in the Cuonadong dome, located nearly 40 km to the South with respect to the Yalaxiangbo dome point out an older activation of the lower ductile shear zone (ca. 25-20 Ma) and a migration of the normal shearing towards the North. This caused an earlier exhumation of the Cuonadong dome with respect to the Yalaxiangbo dome, with similar mechanisms. The two detachments are later folded during the latest stages of exhumation of the domes. New data point out that age of normal shearing not only varies from West to East (Iaccarino et al., 2017; Kellet et al., 2019) but varies along the same vertical section from ductile to brittle and along a N-S direction showing younger ages to the North in the NHGD.

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Cottle J.M. et al. (2015) - Rongbuk re-visited: Geochronology of leucogranites in the footwall of the South Tibetan detachment system, Everest region, southern Tibet. Lithos, 227, 94-106.

Iaccarino S. et al. (2017) - Pressure-Temperature-Deformation-Time Constraints on the South Tibetan Detachment System in the Garhwal Himalaya (NW India). Tectonics, 36, 2281-2304.

Kellett D.A. & Grujic D. (2012) - New insight into the South Tibetan detachment system: Not a single progressive deformation. Tectonics, 31, TC2007.

Tracking melt migration pathways across the continental crust using sillimanite-gneiss

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Keywords: melt migration, sillimanite, melt-rock interaction.

The activity of high-strain deformation zones in the deeper structural levels of the continental crust not only has significant rheological consequences but also enhances melt extraction and migration. As melt migrates from one geochemical environment to another, it reacts with the host rocks, considerably changing their composition (Daczko & Piazolo, 2022). Thus, such reactions lead to lithological and geochemical differentiation of the continental crust from the micro- to macroscale. However, recognition of areas of significant melt migration remains elusive.

The Valpelline Series within the Dent Blanche Tectonic System in the Western Italian Alps is a key target area for investigating processes such as partial melting and melt migration during long-lasting lithospheric extension in Permian times. In the Valpelline Series sillimanite-gneiss is a common rock type showing a distinctive mineral modal composition, with up to ~40 vol% sillimanite and ~30 vol% garnet. At map- and mesoscale the sillimanite-rich S3 foliation can be traced as discrete domains corresponding to the axial plane of late-stage D3 folds that deform the regional migmatitic S2 foliation (Caso et al., 2024a, 2024b). Quantitative crystallographic orientation data on sillimanite-gneiss show microstructures indicative of synchronous melt-mineral reactions and deformation: (i) sillimanite along the S3 grows as prismatic undeformed crystals, through rigid body rotation during melt flow; (ii) quartz within the leucosomes marking the S3 is also undeformed, lacking crystallographic preferred orientation and internal deformation, indicating crystallization from a melt; (iii) garnet shows an elongated shape given by melt-driven dissolution-reprecipitation processes and has no preferred crystallographic orientation.

The strong modal enrichment in sillimanite and garnet is due to a melt-rock interaction process during melt flow, coupled with considerable melt extraction during the development of the S3 sillimanite-rich axial plane foliation. We propose a model in which sillimanite-gneiss and its S3 foliation can be used to trace the melt pathways that may have been exploited by the melt to migrate from the deep crust to shallower crustal levels.

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Caso F. et al. (2024b) - Combining traditional and quantitative multiscale structural analysis to reconstruct the tectono-metamorphic evolution of migmatitic basements: the case of the Valpelline Series, Dent-Blanche Tectonic System, Western Alps. Journal of Structural Geology, 182(1),105099, https://doi.org/10.1016/j.jsg.2024.105099.

Daczko N.R. & Piazolo S. (2022) - Recognition of melferite–A rock formed in syn-deformational high-strain melt-transfer zones through sub-solidus rocks: A review and synthesis of microstructural criteria. Lithos, 430, 106850, https://doi.org/10.1016/j.lithos.2022.106850.

Early Stages of Mountain Building in the Central Mediterranean: The Collision of the Calabrian Arc and Mediterranean Ridge

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Keywords: Calabrian Arc, Mediterranean Ridge, Kefalonia Transfer Zone.

In convergent plate boundaries, the pre-collisional stages, when most of the oceanic crust has already been subducted and remnant ocean basins form, are often hidden/eroded, and reshaped within the tectonic units forming orogenic wedges. The central-eastern Mediterranean Sea is one disputed remnant ocean basin ideal for reconstructing these pre-collisional and early collisional stages of mountain chain formation. This area is home to the Calabrian and Hellenic Arcs and two subduction systems along the irregular Africa/Adria-Eurasia plate boundary. The two opposite-verging accretionary wedges, i.e., the Mediterranean Ridge and the Calabrian Arc wedge (Minelli & Faccenna, 2010; Polonia et al., 2011), are separated by the Ionian Abyssal Plain. The latter is known to be affected by deep transpressive faults aligned with the Kefalonia Transfer Zone, which likely inherited earlier extensional structures (Gallais et al., 2012). As the Ionian Abyssal Plain narrows towards the northeast, the two wedges face each other and collide. We integrate multichannel seismic reflection profiles and bathymetric data to reconstruct the structural evolution and kinematics of the collision zone between the two wedges. Our finding suggests that the progressive convergence between the Calabrian Arc and the Mediterranean Ridge resulted in varying deformation rates, fold geometries, and tectonic styles across the study area. Specifically, seismo-stratigraphic analyses and kinematic reconstructions suggest that during the Pliocene, the Mediterranean Ridge experienced dominant outward growth. However, from the Middle Pleistocene onwards, deformation related to the Calabrian Arc became predominant, possibly linked to its clockwise rotation and southeastward migration. More interestingly, NE-SW-oriented positive inverted faults aligned with the Kefalonia Transfer Zone have recently affected the Calabrian Arc-Mediterranean Ridge contact zone. This suggests that the inherited crustal structures of the subducting Ionian lithosphere initially formed during Tethyan rifting strongly influence the style and localization of compressive and transpressive deformation in this area. These findings shed new light on the early-stage collision of the orogenic wedge and provide a new conceptual model for the evolution of subduction margins transitioning from oceanic subduction to continental collision, with an active role of the lower plate in shaping the collisional area. This also enhances our understanding of the complexities of the pre-collisional setting of Cenozoic-Mesozoic and older collisional orogens.

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Polonia A. et al. (2011) - The Calabrian Arc subduction complex in the Ionian Sea: regional architecture, active deformation and seismic hazard. Tectonics, 3, 1e28, https://doi.org/10.1029/2010TC002821.

Gallais F. et al. (2012) - Two-stage growth of the Calabrian accretionary wedge in the Ionian Sea (Central Mediterranean): constraints from depht-migrated multichannel seismic data. Mar. Geol., 326-328, 28-45, https://doi.org/10.1016/j.margeo.2012.08.006.

The Lower Paleozoic to Permian evolution of the Dora-Maira Massif basement (Western Alps), revealed by zircon geochronology

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Keywords: Dora-Maira, U-Pb geochronology, tectonics.

Over the past five decades, a substantial amount of geochronological data has been acquired from the continental-derived units of the Western Alps, providing constraints on both the ages of magmatic protoliths and the deposition ages of (meta)sedimentary sequences. These data reveal the long and complex pre-Alpine evolution of the crystalline basements now stacked in the Alpine orogen. Among these units, the Dora-Maira Massif (Sandrone et al., 1993) stands out as the largest and most intensively studied basement-dominated unit, particularly following the discovery of coesite-bearing UHP rocks (Chopin, 1984). Nevertheless, major uncertainties remain regarding the protolith ages and mutual relationships among the various lithologies, with only a limited number of available dedicated studies (Bussy & Cadoppi, 1996; Nosenzo et al., 2024).

In this study, we present new LA-ICP-MS U-Pb zircon ages and whole-rock geochemical data from orthogneiss samples collected in the central-northern Dora-Maira Massif, as part of the Geological Map of Italy CARG project (sheet 172 “Pinerolo,” 1:50,000 scale). Our results document the presence of late Ediacaran–Cambrian magmatic protoliths, later overprinted by at least three orogenic cycles (Cenerian, Variscan, and Alpine), as indicated by the emplacement of younger magmatic rocks related to the Ordovician–Silurian cycle and Permian magmatism.

The aim of this contribution is twofold: (i) presenting new geochronological and geochemical constraints on meta-intrusive rocks of the Dora-Maira Massif, and (ii) interpreting this dataset within a broader geodynamic framework, emphasizing the significant role of Lower Paleozoic tectonics in shaping the Dora-Maira basement.

Bussy F. & Cadoppi P. (1996) - U-Pb zircon dating of granitoids from the Dora-Maira massif (western Italian Alps). Schweizerische Mineralogische und Petrographische Mitteilungen, 76, 217-233.

Chopin C. (1984) - Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. Contributions to Mineralogy and Petrology, 86, 107-118.

Nosenzo F. et al. (2024) - Tectonic architecture of the northern Dora-Maira Massif (Western Alps, Italy): field and geochronological data. Swiss Journal of Geosciences, 117(1), 6.

Sandrone R. et al. (1993) - The Dora-Maira Massif. In Pre-Mesozoic geology in the Alps, 317-325. Berlin, Heidelberg: Springer Berlin Heidelberg.

Protolith age of meta-mafic rocks from the Pinerolo-Sanfront Unit, Dora-Maira Massif, Western Alps

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Keywords: Dora-Maira, U-Pb geochronology, geochemistry.

Metamorphic rocks, with a magmatic protolith, are widespread in the continental basement units of the Western Alps (Beltrando et al., 2010), providing key insights into past tectonic processes. Moreover, meta-mafic rocks building up the metamorphic basements are excellent markers of past geodynamic events, since they provide insights on the geotectonic setting of their emplacement based on whole-rock and trace element geochemistry (Chocyk-Jaminski & Dietsch, 2002). In this study, we report new occurrences, field observations, geochemical, and geochronological data for meta-mafic rocks in the northern Dora-Maira Massif (Western Alps) for both polycyclic Muret Unit (Nosenzo et al., 2022) and monocyclic Pinerolo-Sanfront Unit (Vialon, 1966). We collected different types of meta-mafic rocks based on their structural position and mapping occurrence and performed whole-rock geochemistry to characterize different bodies of meta-mafic rocks inside both Muret and Pinerolo-Sanfront Units. U–Pb zircon LA-ICP-MS dating on a sample from the Pinerolo-Sanfront Unit yielded a Cambrian crystallization age for the photolith. These findings challenge the traditional, and current, interpretation of the Pinerolo-Sanfront Unit build-up of exclusively Permo-Carboniferous rocks, leading to major implications for its geological evolution and for the Lower Palaeozoic tectonics of this segment of Western Alps.

Beltrando M. et al. (2010) - (Ultra-) High-pressure metamorphism and orogenesis: an Alpine perspective. Gondwana Research, 18(1), 147-166.

Chocyk-Jaminski M. & Dietsch C. (2002) - Geochemistry and tectonic setting of metabasic rocks of the Gneiss Dome Belt, SW New England Appalachians. Physics and Chemistry of the Earth, Parts A/B/C, 27(1-3), 149-167.

Nosenzo F. et al. (2022) - A window into an older orogenic cycle: P–T conditions and timing of the pre-Alpine history of the Dora-Maira Massif (Western Alps). Journal of Metamorphic Geology, 40(4), 789-821.

Vialon P. (1966) - Etude géologique du massif cristallin Dora-Maira: Alpes cottiennes internes: Italie (Doctoral dissertation, Université de Grenoble).

A reappraisal of the Late Cretaceous subduction to obduction cycle in Oman: new structural, thermobarometric and geochronological insights from the Jabal Akhdar tectonic window

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Keywords: subduction-obduction cycle, Oman Mountains.

The geodynamic mechanisms shaping the Oman Mountains have long been studied to better understand the Late Cretaceous subduction-obduction cycle affecting the northeastern Arabian Plate. However, many questions remain about the number and polarity of the involved subduction zones, the extent of subduction and the metamorphic conditions experienced. To address these issues, we examined the Jabal Akhdar tectonic window—a key yet understudied area where subduction-related compression, metamorphism and obduction are recorded with limited syn-orogenic overprint.

In Jabal Akhdar, we identified two regional deformational phases, D1 and D2, each with distinct macro-, meso-, and microstructures, used to constrain their metamorphic histories. D1 involves brittle-ductile to ductile top-to-the northern quadrants S-C foliation, thrusts and asymmetric folds affecting both the Neoproterozoic metasedimentary basement and the overlying Permian carbonates. D2 caused localized SW-directed shortening, characterized by folds, thrusts, duplexes, and mylonitic shear zones mainly in Mesozoic carbonates beneath the Semail Ophiolite.

To determine the pressure and temperature (P–T) conditions, we used a multidisciplinary approach. Chlorite–white mica–quartz–water multiequilibrium thermobarometry on D1 syn-kinematic minerals integrated with Raman Spectroscopy on carbonaceous material indicate conditions of about 350°C and 0.6 GPa, consistent with lower-blueschist facies deformation. D2 occurred at lower-grade greenschist facies conditions, as evidenced by the microstructures of recrystallized calcite in mylonitic shear zones.

Cross-cutting relationships suggest D1 is post-Permian to Late Cretaceous, with D2 overprinting D1 structures. U-Pb dating on calcite/aragonite is ongoing to exactly pinpoint the ages of these deformation phases.

While D2 in Jabal Akhdar is widely attributed to Late Cretaceous SW-directed obduction of the Semail Ophiolite (e.g.: Le Metour et al., 1990), D1 is traditionally considered Palaeozoic or remains loosely constrained. Recent work (Zuccari et al., 2023) proposes D1 as a Cretaceous blueschist facies contractional stage. These findings challenge the view of a largely undeformed, non-metamorphic record in Jabal Akhdar and raise questions about the role of the northeastern Arabian margin in Late Cretaceous subduction and obduction processes.

Le Métour J. et al. (1990) - Subduction and obduction: two stages in the Eo-Alpine tectonometamorphic evolution of the Oman Mountains. Geological Society, London, Special Publications, 49(1), 327-339, https://doi.org/10.1144/GSL.SP.1992.049.01.20.

Zuccari C. et al. (2023) - Forming and preserving aragonite in shear zones: First report of blueschist facies metamorphism in the Jabal Akhdar Dome, Oman Mountains. Geology, 51(5), 454-459, https://doi.org/10.1130/G51079.1.

New insights on the pre-Variscan metamorphic evolution of the Ötztal Nappe: a case study from the Reschen Pass area (Eastern Alps, N Italy)

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Keywords: Austroalpine, magmatism, mapping.

The tectonometamorphic units of the Austroalpine Domain of the Eastern Alps experienced heterogeneous Alpine metamorphism, locally so faint that geological features related to older orogenic events remain intact. A notable example is the Ötztal-Stubai Complex (extended for ca. 50 km by 20 km area across northernmost Italy and Austria) which preserves structures and mineral assemblages from the earlier Variscan orogeny (Carboniferous to Permian; e.g., Thöni, 1980; Hoinkes et al., 1997), as well as relics of events of Caledonian age (Ordovician to Silurian; e.g., Schweigl, 1995; Thöni et al., 2008), offering a key record for understanding the pre-Alpine geological history.

Such is the case of a relatively small area (~25 km²) near the village of Reschen (South Tyrol, NE Italy), where possible pre-Variscan features - including the magmatic rocks of the Klopaier Pluton, its contact metamorphic aureola, and migmatites - are hosted within country rocks that display Variscan mineral assemblages and a very heterogeneous deformational overprint.

New detailed field mapping (CARG Project - 011 Malls sheet) revealed that the pluton has little or no deformation, behaving locally as a rigid body and preserving within its strain shadow evidence of primary contacts with the surrounding host rocks. There, relics of cordierite possibly mark the contact aureola and migmatites (dominantly metatexites) result from partial melting of the same host rocks. Pegmatite dikes, probably related to highly evolved fluids derived from the Klopaier Pluton, occur both within the pluton and in the host rocks, and yield ages ranging between 490 and 413 Ma (Schweigl, 1995). This suggests that the observed structural configuration was already established around 460 Ma. A new U-Pb zircon age for the Klopaier Tonalite indicates a younger age of 460 Ma, consistent with the ages obtained from associated pegmatitic dikes. What remains uncertain, however, is the sequence of events - essentially a geological "chicken or egg" dilemma: did the pluton intrude into already formed and cooled migmatites, or did its emplacement and associated heat trigger partial melting in the surrounding rocks? To solve this, new ages associated with their geochemical data will be collected, with the aim of providing significant insights into the pre-Alpine evolution of the Austroalpine Domain.

Hoinkes G. et al. (1997) - Metagranitoids and associated metasediments as indicators for the pre-Alpine magmatic and metamorphic evolution of the western Austroalpine Ötztal Basement (Kaunertal, Tirol). Schweizerische Mineralogische und Petrographische Mitteilungen, 77, 299-314.

Schweigl J. (1995) - Neue geochronologische und isotopengeologische Daten zur voralpidischen Entwicklungsgeschichte im Ötztalkristallin (Ostalpen). Jb. Geol. Bundesanstalt, 138, 131-149.

Thöni M. (1980) - Distribution of pre-Alpine and Alpine metamorphism of the southern Ötztal Mass and the Scarl Unit, based on K/Ar age determinations. Mitt. österr. geol. Ges, 71(72), 139-165.

Thöni W.F. et al. (2008) - The metamorphic evolution of migmatites from the Ötztal Complex (Tyrol, Austria) and constraints on the timing of the pre-Variscan high-T event in the Eastern Alps. Swiss J. Geosc., supplement 1, 111-126, https://doi.org/10.1007/s00015-008-1290-0.

Exhumation of Continental UHP-rocks: Insights from Phengite and Zircon Geochronology in the Tso Morari Massif

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Keywords: rubidium–strontium, Himalaya, in situ geochronology.

Metamorphic assemblages in mafic eclogite from the Himalayan ultra-high-pressure (UHP) Tso Moriri Massif (TMM; commonly misspelt Tso Morari in the literature) indicate peak pressure–temperature (P–T) conditions of ~2.6–2.8 GPa and 600–620 °C (O'Brien, 2019). However, significantly higher peak pressures > 4.5 GPa have also been proposed (O'Brien, 2019). Various geochronological methods constrain the timing of prograde UHP metamorphism to between ~57 Ma and 53 Ma, with eclogite-facies conditions persisting until ~47–43 Ma (Bidgood et al., 2024). Nevertheless, early geochronological studies suggest that amphibolite-facies conditions were reached by ~47 Ma, implying very rapid decompression (De Sigoyer et al., 2000).

Despite this, few studies have examined the structural pathways that may have facilitated the exhumation of the TMM to mid-crustal levels. To reconcile the apparently diachronous and inconsistent age data and to better understand the exhumation history of the TMM, we conducted U–Pb zircon and rutile dating on eclogites, along with in situ Rb–Sr white mica dating on both eclogites and mylonites from the massif's upper shear zone.

Our U–Pb zircon data confirm the persistence of eclogite-facies conditions until ~48 Ma. The in situ Rb–Sr dating of white mica from the shear zone yields ages of 38 ± 7 Ma and 32 ± 3 Ma. Complementary geothermometry by Raman spectroscopy of carbonaceous material and quartz microstructure analyses indicate deformation temperatures in the shear zone between 450 and 550 °C (Long et al., 2020).

We propose that shearing along the top of the TMM occurred between ~38 and 32 Ma, marking a transition from amphibolite to greenschist-facies conditions of the UHP terrane. This shearing phase was likely distinct from the earlier exhumation process, which involved rapid decompression followed by rapid cooling.

Bidgood A.K. et al. (2024) - The geodynamic significance of continental UHP exhumation: New constraints from the Tso Morari Complex, NW Himalaya. Tectonics, 43, e2023TC007976, https://doi.org/10.1029/2023TC007976.

de Sigoyer J. et al. (2000) - Dating the Indian continental subduction and collisional thickening in the northwest Himalaya: Multichronology of the Tso Morari eclogites. Geology, 28(6), 487-490, https://doi.org/10.1130/0091-7613(2000)28<487:DTICSA>2.0.CO;2.

Long S.P. et al. (2020) - Thermometry and microstructural analysis imply protracted extensional exhumation of the Tso Morari UHP nappe, northwestern Himalaya: Implications for models of UHP exhumation. Tectonics, 39, e2020TC006482, https://doi.org/10.1029/2020TC006482.

O'Brien P.J. (2019) - Tso Morari coesite eclogite: pseudosection predictions v. the preserved record and implications for tectonometamorphic models. Geological Society, London, Special Publications, 474, 5-24, https://doi.org/10.1144/SP474.16.

Reworking the middle crust during exhumation: Insights from HT-LP shear zones in the Greater Himalayan Sequence, Eastern Nepal

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Keywords: Himalayan tectonics, shear zone, monazite petrochronology.

The Greater Himalayan Sequence (GHS) constitutes the high-grade metamorphic core of the Himalaya and offers an exceptional natural laboratory for investigating crustal processes, due to its remarkable 3D exposure. Traditionally viewed as a coherent tectonic unit, recent multi-scale and multi-disciplinary studies challenge this interpretation, suggesting a more complex, composite architecture (Carosi et al., 2010; Montomoli et al., 2013, 2015). This study contributes to this evolving perspective by examining the role of high-temperature/low-pressure (HT-LP) ductile shear zones in accommodating deformation within the GHS of Eastern Nepal. We integrate field observations, microstructural analysis, phase equilibria (pseudosection and iterative thermodynamic) modelling, and monazite petrochronology to characterize normal-sense shear zones (with both top-to-the-S and top-to-the-N) affecting garnet–sillimanite- and cordierite-bearing anatectic paragneiss. These shear zones formed under upper amphibolite facies conditions (~700°C), as evidenced by syn-kinematic mineral assemblages and quartz–feldspar dynamic recrystallization. P–T modelling reveals a pre-shearing metamorphic peak at upper amphibolite to granulite facies conditions, under melt-bearing regimes, followed by decompression and minor cooling during mylonitic shearing.

Our results highlight progressive strain localization within migmatitic rocks, post-dating melt extraction, spanning from the Oligocene to Miocene. These findings offer new constraints on the role of HT-LP extensional shear zones in driving the exhumation and thinning of the GHS, with broader implications for middle-lower crustal behavior in collisional orogens.

Carosi R. et al. (2010) - Late Oligocene high-temperature shear zones in the core of the Higher Himalayan Crystallines (Lower Dolpo, Western Nepal). Tectonics, 29, TC4029.

Montomoli C. et al. (2013) - Tectonometamorphic discontinuities within the Greater Himalayan Sequence in Western Nepal (Central Himalaya): insights on the exhumation of crystalline rocks. Tectonophysics, 608, 1349-70.

Montomoli C. et al. (2015) - Tectonometamorphic discontinuities in the Greater Himalayan Sequence: a local or a regional feature? Geol. Soc., London, Sp. Publ., 412, 25-41.

Geological implications of a new P and S wave finite-frequency teleseismic tomography of the mantle in the greater Alpine region

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Keywords: Alps, tectonics, slab interaction.

The relative motion between the Adriatic and European plates during the Cenozoic induces interference between the Alpine slab and the Apenninic and Dinaric slabs, with potential first-order implications for the tectonic evolution of the entire greater Alpine region. To shed light on this issue, we present P- and S-wave velocity models of the mantle based on a finite-frequency teleseismic tomography and discuss the relationships between high-velocity anomalies related to slabs and the prominent low-velocity anomalies in the upper mantle imaged beneath the greater Alpine region. Because of slab interference, low-velocity anomalies of different origins, either due to asthenospheric upwelling or slab fluids, coexist in nearby regions of the Alpine upper mantle. We demonstrate that slab interference controls the location of major tectonic boundaries of the Alpine belt and the characteristics of volcanism during its Cenozoic evolution. Similar complexities may characterize other sites of the Alpine-Himalayan orogen where the interplay between opposite-dipping slabs is suggested by geophysical and geological data.

Dating deformation in crustal-scale shear zones: insights from the Himalayas and the Alps

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Keywords: shear zones, petrochronology, $^{40}Ar/^{39}Ar$ dating.

Understanding when and how shear zones evolve is critical for the reconstruction of the dynamics of collisional orogens. Shear zones are indeed key structures controlling relative movements among tectonometamorphic units both during prograde and retrograde paths, yet their complex histories of deformation, metamorphism, and fluid infiltration often challenge chronological reconstruction. In this contribution, I illustrate how an integrated petrochronological approach, combining $^{40}Ar/^{39}Ar$ geochronology with detailed microstructural and microchemical analyses, can robustly constrain the timing of deformation in crustal-scale shear zones from the Himalayan and Alpine collisional belts.

The evolution of shear zones is governed by several factors, including the deformation regime, flow kinematics, temperature, strain rate and magnitude, and the rheological properties of the involved rocks. Shear zones are frequently preferred paths for fluid infiltration that promotes dissolution–precipitation processes, which in turn influence both deformation mechanisms and isotope systematics. This complexity makes the interpretation of the geochronological data challenging and can only be resolved by combining isotopic data with microstructural analysis and petrology.

Here, I review the challenges of dating polyphasic activity of crustal scale shear zones mainly with the use of the $^{40}Ar/^{39}Ar$ method on syn-kinematic micas. Step-heating analyses provide information on the degassing behaviour of different mineral generations, allowing the identification of distinct compositional fingerprints associated with specific mineral generations. Combined EPMA mapping and geochronological analyses reveal that deformation-related mica recrystallization often occurs via fluid-assisted dissolution–precipitation, producing chemically and texturally heterogeneous domains at scales of a few tens of microns or less. These microscale processes have significant implications: without careful petrographic and microchemical analyses, Ar isotope data, but also data from other geochronometers, may reflect mixtures of different generations rather than discrete tectonometamorphic events.

Case studies from the Himalayas and the Alps demonstrate that syn-kinematic mica growth, relict mineral preservation, and late-stage overgrowths can coexist at the scale of hand samples, and that only an integrated, multiscale approach enables their correct chronological interpretation. Moreover, combining $^{40}Ar/^{39}Ar$ data with independent P–T constraints allows reconstruction of P–T–d–t paths and quantification of the rates and durations of deformation processes across orogenic belts.

Results from shear zones in the Garhwal Himalaya and the Central Alps highlight the importance of integrating field based geological and structural observations, petrography, microanalysis, and multichronometric geochronology to reconstruct the long-lived evolution of crustal-scale shear zones and the role they played in the evolution of collisional orogens.

Decoding the multi-stage evolution of the South Tibetan Detachment System in Central Nepal (Himalaya)

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Keywords: Himalaya, shear zone, STDS.

The South Tibetan Detachment System (STDS) is one of the most striking examples of a low-angle normal fault on Earth, juxtaposing the lower high-grade metamorphic rocks of the Greater Himalayan Sequence with the overlying very low-grade to unmetamorphosed rocks of the Tethyan Himalayan Sequence.

In its most studied section, near Mt. Everest (Nepal Himalaya), the STDS consists of an upper brittle fault and a lower ductile shear zone (Carosi et al., 1998; Searle, 1999). However, along several transects across Central Nepal, the brittle fault has not been identified.

Detailed microstructural analyses on oriented thin sections provide new insights into the development and tectonic evolution of the STDS in this region.

By integrating microstructural data with crystallographic preferred orientation, paleopiezometry, and kinematic vorticity analyses, a complex, multistage tectonic history has been revealed (Nania et al., 2022, 2024).

Two distinct stages of non-coaxial deformation have been identified, during which the STDS deformed progressively from deeper to shallower structural levels under decreasing temperature conditions.

The first stage, occurring at deeper structural levels, was associated with low differential stress (< 15 MPa), whereas the second stage was characterized by higher differential stress (> 100 MPa).

This increase in flow stress during cooling is interpreted as reflecting progressive exhumation of the STDS, during which strain hardening occurred, allowing ductile shearing to persist at shallower levels without localization of the upper brittle fault.

Carosi R. et al. (1998) - The South Tibetan detachment system in the Rongbuk valley, Everest region. Deformation features and geological implications. Journal of Asian Earth Sciences, 16, 299-311.

Nania L. et al. (2022) - Multi-stage evolution of the South Tibetan Detachment System in central Himalaya: insight from carbonate-bearing rocks. Journal of Structural Geology, 158, 104574.

Nania L. et al. (2024) - Calcite fabric development in calc-mylonite during progressive shallowing of a shear zone: an example from the South Tibetan Detachment system (Kali Gandaki valley, Central Nepal). Tectonophysics, 872, 230176.

Searle M.P. (1999) - Extensional and compressional faults in the Everest–Lhotse massif, Khumbu Himalaya, Nepal. J. Geol. Soc. London, 156(2), 227-240.

Early-eocene to late-Oligocene kinematics of the western Mediterranean microplates: New insights from multiscale GIS-based investigations of variously aged mylonitic rocks

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Keywords: multiscale geological data analysis, vorticity analysis, Mediterranean geodynamics.

Within the broader Alpine-Himalayan system, a surely peculiar role is played by the Apennine orogenic system. This orogenic system is, in fact, characterized by a main trend of the orogenic belt perpendicular to the main Alpine arc; moreover, it is also locally characterized by strongly arcuate zones controlled by the movement of ribbon-like microplates that have driven, since the late Paleozoic, the break-up of the former Varisian chain.

The present contribution updates and integrates meso- and micro-structural data from three, differently aged, crustal-scale mylonitic shear zones that have recorded the geodynamic evolution of one of the key sectors of the western Mediterranean geodynamics from the late Eocene up to the Oligocene-Miocene boundary (i.e., the southern sector of the Calabrian Peloritani Composite Terrane - sCPCT).

The newly obtained as well as the updated one's fabric-related parameters have been yielded through a multiscale analytical procedure, starting from new meso-structural driven sampling collections, followed by the automated grain-boundaries digitation (i.e., Visalli et al., 2021; Ortolano et al., 2021) of opportunely selected mylonites at the microscale. The overall obtained multiscale dataset was useful, then: a) to better constrain the main structural setting of the investigated shear zones, restoring, where possible, the original bedding at the time of the activation of the mylonitic process; b) to highlight the relative percentage of pure- vs. simple-shear component, as well as the prevalent kinematics; c) to obtain the average grain sizes of the syn-mylonitic quartz grains, useful to estimate new shear strain rates and, in turn, to calculate the relative displacement and/or the definition of the exhumation mechanisms.

Last, but not least, a quantitative image-assisted analysis (i.e., Ortolano et al., 2018) permitted the syn-shearing metamorphic equilibria to be obtained, useful in turn to better constrain the PT conditions of the mylonitic process through isochemical section computation (Xiang & Connolly, 2021).

Obtained results confirmed the difficulty of treating the entire Calabrian microplate as a unique ribbon-like orogenic segment formed, exclusively, at the expense of the southern European Variscan chain margin and, in particular, from the Sardinia-Corsica block. This evidence reinforced the hypothesis of a present-day composite orogenic segment where at least two microplates started to differentiate since the later stages of the Variscan orogenesis, before being merged again from the late Oligocene with the embryonic deep-seated activation of the Apennine crustal thickening stage, which gave rise to the present-day joined orogenic segment.

Ortolano G. et al. (2018) - Quantitative X-ray Map Analyser (Q-XRMA): A new GIS-based statistical approach to Mineral Image Analysis Computers and Geosciences, 115, 56-65, https://doi.org/10.1016/j.cageo.2018.03.001.

Ortolano G. (2021) - ArcStereoNet: A New ArcGIS® Toolbox for Projection and Analysis of Meso- and Micro-Structural Data. ISPRS Int. J. Geo-Inf., 10, 50, https://doi.org/10.3390/ijgi10020050.

Xiang H. & Connolly J.A.D. (2021) - GeoPS: An interactive visual computing tool for thermodynamic modelling of phase equilibria. Journal of Metamorphicy, 1-13, https://doi.org/10.1111/jmg.12626.

Visalli R. et al. (2021) - Micro-Fabric Analyzer (MFA): A New Semiautomated ArcGIS-Based Edge Detector for Quantitative Microstructural Analysis of Rock Thin-Sections. ISPRS Int. J. Geo-Inf., 10, 51, https://doi.org/10.3390/ijgi10020051.

From shortening to extension of the Tethyan Himalaya: Reconstructing the northern Indian passive margin

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Keywords: Tethyan Himalaya, cross-section balancing, thrust tectonics.

The Himalayan orogeny, initiated by the collision between the Indian and Eurasian plates at around 50 Ma, stands as a fundamental example of continental collision and large-scale crustal shortening. Despite the critical role played by the Tethyan Himalaya fold-and-thrust belt in this context, the amount of crustal shortening accommodated within this domain remains poorly constrained. Balanced geological cross-sections are scarce, and often outdated, while the existing shortening estimates vary significantly, typically ranging from ~100 km to ~250 km (e.g., Ratschbacher et al., 1994). This uncertainty limits the ability to test tectonic models for the India-Asia collision and complicates efforts to reconcile geological shortening estimates in the Tethyan Himalaya with paleomagnetic reconstructions, which predict up to four thousand kilometers of plate convergence since 60 Ma (Poblete et al., 2021). The Tethyan Himalaya Sequence (THS) is located between the South Tibetan Detachment System (STDS) to the south and the Indus-Yarlung Tsangpo Suture Zone to the north. THS consists of a Cambrian to Eocene sedimentary succession recording the evolution of the northern Indian passive margin, from early Permian rifting to passive drift. The STDS, evolving from a ductile to brittle shear zone, and the North Himalayan Gneiss Domes (NHGD), recording Late Miocene mid-crustal exhumation, both document the effects of mid-crustal flow associated with the development of a low-viscosity channel bounded by the STDS and the Main Central Thrust Zone (MCTZ) (Godin et al., 2006). The south-vergent Gyirong-Kangmar Thrust (GKT), located south of the NHGD, is interpreted to place pelagic Mesozoic strata over shelf sediments. Its existence is inferred from this transition, which may reflect a major change in crustal thickness. Ratschbacher et al. (1994) suggested the GKT is a basement-involved thrust, although it is not apparent in the INDEPTH seismic profile (Hauck et al., 1998). This study refines crustal shortening estimates across the THS and constrains the geometry of the basal detachment, providing new insights into the early structural evolution of the Himalayan orogen. Balanced and restored cross-sections were developed using 3DMOVE software, integrating geological mapping, field observations, and subsurface data. The study area extends longitudinally between the Kampa and Kangmar domes, where extensional structures related to the STDS locally overprint earlier thrust-related fabrics, necessitating careful structural restoration. The results document significant crustal shortening and highlight a tectonic transition, supporting the interpretation that the compressional structures were overprinted during Miocene by low-angle extensional shear zones. Furthermore, the updated shortening estimates contribute to reconstructing the original length of the northern Indian passive margin prior to collision, offering critical constraints for the Himalayan tectonic evolution.

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Pre-Variscan evolution of the Oetztal-Stubai Complex (Eastern Alps)

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Keywords: Gondwana, austroalpine, petrology.

The Oetztal-Stubai Complex (OSC, Eastern Austroalpine) is one of the largest tectonic units of the Alps extending between western Austria (Tyrol) and northern Italy (Autonomous Province of Bozen/Bolzano). The OSC is a polymetamorphic unit made of crystalline basement consisting of metasedimentary rocks hosting numerous bodies of metagranitoids and metabasic rocks, along with subordinate metacarbonates and ultramafics. The Alpine metamorphism increases in temperature from 300°C in the north-west up to 500°C in the south-east (Raso et al., 2025).

Pre-Alpine evolution is testified by Cambrian mafic to ultramafic cumulates preserved within the Central Metabasite Zone (CMZ) (Miller & Thöni, 1995; Konzett et al., 2005); an Ordovician high temperature event resulting in widespread intrusions of granitoids and partial melting of metapelites (*e.g.* Winnebach migmatites); occurrence of Variscan eclogites in the CMZ and pervasive re-equilibration under amphibolite facies conditions. Extensive field work, microstructural and petrological analyses, and radiometric dating are being carried out in the Central Metabasite Zone, specifically around the locality of Längenfeld (Milchenkar and Luibiskogel areas). Here, the Sulztal type S granite, for which we obtained U-Pb zircon ages of 463.7 ± 1.1 Ma, flanks the metabasic complex consisting in abundant mafic eclogites enveloping ultramafic protoliths locally showing well preserved cumulitic textures. The Milchenkar area hosts the majority of these preserved protoliths, mainly cumulitic olivine gabbros and subordinated troctolites and gabbros, while the Luibiskogel area is characterized by higher degrees of deformation and metamorphism, resulting in the complete eclogitization of the mafic and ultramafic cumulates, and by the widespread occurrence of eclogite-derived leucosomes. Whole rock and mineral chemistry of magmatic minerals, along with trace element composition of Ti-rich amphibole (up to 5% TiO_2) suggest a mildly alkaline parental melt. Different degrees of metamorphism affect the cumulitic protoliths: olivine gabbro occasionally display the destabilization at high pressure conditions of anorthite-rich plagioclase to omphacite + corundum intergrowths bordered by garnet; corundum-bearing coronas made of sodic amphibole also occur in troctolites around orthopyroxene rims growing on olivine. Plagioclase is also often characterized by granoblastic textures with increased anorthite content in the rims, implying a static phase of recrystallization at high temperature. Mafic eclogites show complex textures with the presence of at least two generations of garnet and omphacite or Na-amphibole. Notably, previously unreported inclusions of corundum and Mg-staurolite in eclogitic garnet have been found.

The occurrence of closely associated markers of pre-Variscan processes, reflecting a wide range of P-T conditions, offers a remarkable opportunity to investigate and reconstruct the late stages of Gondwana's evolution.

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Raso G. et al. (2025) - Diabase is petrologists best friend: quantitative P-T constraints on the NW-Se trending Eoalpine metamorphic gradient in the western Austroalpine nappe stack (Ötztal nappe, Texel nappe, Silvretta nappe) using metamorphosed mafic dikes. Austrian Journal of Earth Sciences, 118(1), 75-94.

Micas as archives of metamorphic reworking: a case study from the migmatite gneiss of the Valpelline Series (Dent-Blanche Tectonic System, Western Alps)

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Keywords: $^{39}Ar/^{40}Ar$ stepwise heating method, in situ Rb-Sr geochronology, microstructures.

Micas crystallize over a wide range of magmatic and metamorphic conditions. In crystalline basement rocks, they are the main minerals responsible for defining and supporting foliation. $^{39}Ar/^{40}Ar$ and Rb/Sr geochronological methods allow the dating of mica crystallization. Therefore, a combined approach integrating microstructural, mineral-chemical, and geochronological data of micas enables the reconstruction of metamorphic conditions and their effective correlation with tectonic evolution, more so than is typically possible using accessory phases. However, ages obtained from micas are often younger than expected based on regional constraints, and several processes have been invoked to account for this mismatch. Among them, some suggest prolonged "cooling histories", with direct implications for tectonic process rates and the thermal state of the crust.

We conducted an extensive U/Pb geochronological dataset on various accessory phases such as zircon, titanite, and monazite in migmatites and granulites from the Valpelline Series with these rocks being a portion of the Dent-Blanche Tectonic System in the Western Italian Alps that represents a fragment of pre-Alpine deep continental crust. The results clearly indicate that the high-temperature metamorphic event was restricted to the Early Permian. In contrast, ages obtained from individual biotite crystals, using $^{39}Ar/^{40}Ar$ stepwise heating and *in situ* Rb/Sr methods, range between 220 and 160 Ma, well matching with the rutile U/Pb ages. These results appear to support the widely accepted hypothesis—based on similar geochronological interpretations—of a prolonged Permo-Triassic event that characterized the Mesozoic evolution of the Adriatic plate.

However, a detailed compositional analysis of the dated mica grains reveals textural and mineral-chemical variations using EPMA X-ray mapping at various scales. These analyses reveal that the polygenetic micas consist of multiple generations, each chemically distinct. Furthermore, a clear correlation exists between the degree of mineral replacement and the apparent age rejuvenation, suggesting that the younger isotopic signatures reflect metamorphic replacement processes rather than protracted cooling. A critical discussion of this correlation requires a reconsideration of the significance of the obtained ages and the Permo-Triassic event in the Alps. Given the prevalence of zoned and composite micas, the approach presented here offers a valuable framework for reconstructing complex, polyphase metamorphic histories in other orogenic systems worldwide.

Multidisciplinary approach to investigate the tectono-metamorphic evolution at the southern Sesia-Lanzo/Piemonte zone boundary

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Keywords: Alpine subduction, tectonic mélange, eclogite facies transposition.

This contribution proposes a multiscale structural analysis of a key area located in the axial zone of the Alpine chain, close to the triple junction between the Adriatic continental crust (Sesia-Lanzo Zone - SLZ), the eclogitized metaophiolites (Piemonte Zone - PZ) and one of the huge ultramafic bodies of the Alpine subduction complex (Lanzo Massif). This setting offers a unique opportunity to investigate the structuring of a convergent margin at deep structural levels during active convergence and to explore the deformation and metamorphic mechanisms operating between the two facing tectonic domains: the oceanic subducting plate and the continental crust, tectonically sampled from the upper plate. The inferred structural history reveals four groups of superimposed ductile structures in the rocks from the SLZ and PZ (Spalla et al., 1983). Rootless isoclinal folds are associated with a pervasive S_1 foliation. D2 structures are tight to isoclinal folds associated with a dominant S_2 foliation. D3 includes tight to open folds, and D4 gentle folds have sub-vertical axial planes, locally associated with a disjunctive cleavage. This poly-phase tectono-metamorphic history results in a mixing of thin slivers of oceanic and continental eclogitized rocks characterised by peak conditions of approximately T = 520–630 °C and P = 1.8–2.0 GPa (Rebay & Messiga, 2007; Assanelli et al., 2020). The type of tectonic mélanges here described, consisting of continental and oceanic crustal slices with variably serpentinized peridotites, is expected to form in a hydrated mantle wedge during ablative subduction, as shown by 2D numerical simulations of ocean/continent subduction systems (e.g. Roda et al., 2020).

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Thermochronological Constraints for the Evolution of the European Eastern Southern Alps

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Keywords: thermochronology, Eastern Southern Alps, fold and thrust belt.

Late Oligocene and Miocene east-west decoupling of the Alpine retro-wedge evolution along the Giudicarie fault system and the associated late-stage shortening within the eastern Southern Alps (ESA) are key features of the Neoalpine, post-collisional Adria-Europe convergence. A new balanced cross section in the western ESA identifies this area as the zone that accommodated the least amount of north-south shortening within the eastern Southern Alps. Thermochronological data suggest a ~25 Ma onset of exhumation in the Neoalpine fold-and-thrust belt. This requires a longer lasting transfer of shortening from the Eastern Alps, north of the Periadriatic fault system, into the evolving ESA, rather than a single and distinct Middle Miocene shift to a coupled state. Still, the highest exhumation rates are observed between 17 and 10 Ma, linking rapid ESA exhumation to the termination of folding within the Sub-Penninic interior of the Tauern Window (Rudmann et al., 2024). Prior to the Neoalpine evolution, the transpressive Paleogene collision of northeast-Adria and Europe entailed Dinaric top-top-southwest thrusting on the Adriatic microplate. An Eocene antiformal basement structure and an assumed blind fault in the northwestern ESA, revealed by new thermochronological data, mark the northwestern extend of the Dinaric fold-and-thrust belt. Apart from Dinaric and Neoalpine exhumation related cooling, Adria was affected by Eocene to Oligocene subduction-related magmatism, Jurassic extension, middle Triassic strike-slip tectonics, and Permian extension. Each event as well as the Permian to Cretaceous burial resulted in the thermal perturbation of the Adriatic crust and its sedimentary cover. Despite numerous samples from pre-Mesozoic lithologies, nearly no apatite fission-track single-grain ages older than the Middle Triassic are preserved, confirming regional heating into the partial annealing zone. Permo-Mesozoic thermal perturbation and burial allowed long-term residence of the basement top and lower sedimentary cover within this zone, later preserved by rapid Neoalpine exhumation. Time-temperature models on Permian volcanic rocks demonstrate the strong thermal imprint of Triassic magmatism, especially the Ladinian event.

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Thermal analysis of contact metamorphism in shallow crust reveals a regional Oligocene Barrovian gradient in the Sesia-Lanzo Zone, Western Alps

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Keywords: Alpine collision, magma cooling model, numerical simulation.

The Oligocene Biella pluton is part of the Periadriatic magmatic bodies and is intruded into the post-eclogitic continental crust of the Sesia-Lanzo Zone in the western Austroalpine domain of the European Alps. The emplacement age and depth are well constrained between 30 and 31 Ma, and 3 and 8.5 km, respectively (Romer et al., 1996; Berger et al., 2012; Ji et al., 2019; Zanoni et al., 2022). After the emplacement the pluton was rotated of 60–70° about a shallow plunging axis subparallel to the Periadriatic Fault System (Zanoni et al., 2022). This contribution investigates the thermal interaction between the shallow Biella pluton and the Sesia-Lanzo Zone country rocks, which preserve pervasive eclogitic mineral assemblages related to the Alpine subduction. The aim is contributing at the reconstruction the tectono-thermal setting in the shallow crust of the Western Alps during the mature Alpine collision, where the thermal state can be retrieved by comparing PT conditions of contact metamorphism with thermal conditions predicted by numerical model of magma cooling. The contact metamorphism produced various mineral assemblages in the country rocks, and the quantity of contact metamorphic minerals decrease and fade with increasing distance from the pluton margin. Thermometric estimates based on single mineral chemistry and mineral equilibria highlight that in general the contact metamorphic peak temperatures decrease as an inverse function of the ratio between the distance from the pluton and depth. We compared the thermometric estimates with the results from numerical simulations of pluton cooling. We tested three possible regional geothermal gradients of 30, 40, and 50°C/km affecting the country rocks at the time of the pluton emplacement. The distribution of the thermometric estimates with depth and distance from the pluton better matches the models calculated for geothermal gradients > 40°C/km. At the time of Oligocene pluton emplacement, the Sesia-Lanzo Zone was already shallower than 10 km (anchizone) and thus clear metamorphic evidence related to such a regional geothermal gradient is lacking. This geothermal gradient is similar to the gradient related to the regional Barrovian metamorphism affecting the Central Alps between 34 and 27 Ma (i.e., Lepontine dome). We propose that the Oligocene Barrovian gradient, which is well recorded in the Lepontine dome, involved wider areas in the Western Alps than what has been documented so far. Thus, quantifying the thermal interaction of magma emplacement and country rocks can be a reliable method for disclosing regional thermal states of shallow and non-metamorphic continental crust.

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Zanoni D. et al. (2022) - Cooling history of the Biella pluton and implication for Oligocene to Miocene tectonics of the Sesia-Lanzo Zone, Austroalpine, Western Alps. Int. Geol. Rev., 64(2), 203-232, https://doi.org/10.1080/00206814.2020.1845993.

A high-temperature tectonic mélange marking the Variscan suture in the Argentera-Mercantour Massif of Western Alps

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Keywords: Argentera-Mercantour Massif, orogenic suture, Variscan chain.

Variscan rocks in the Alps record processes such as subduction, continental collision, and late-orogenic extension, lasting until the Early Permian, and represent key sources of information on the evolution of the southern Variscan belt. The basement of the Argentera-Mercantour Massif, part of the External Crystalline Massifs, consists of migmatitic metaintrusives and paragneisses, along with mafic and ultramafic lenses or boudins transposed into the Carboniferous high-temperature foliation. Metabasites include amphibolites, eclogites, and granulites, whereas ultramafic rocks are represented by serpentinized peridotites and pyroxenites, often associated with additional lenses of clinopyroxene-, epidote-, and garnet-bearing calc-silicate rocks and marble layers, possibly indicating an oceanic origin. The occurrence of such a high-temperature tectonic mélange in the core of the Argentera-Mercantour Massif supports the presence of a fragmented Variscan suture zone within the pre-Alpine crystalline basement of the Alps. This study presents new data from different localities of the Argentera-Mercantour Massif, focusing on lithostratigraphy, protolith origin, and metamorphic P–T conditions, primarily concerning eclogites, which in most cases have been retrogressed to garnet-bearing amphibolites and only rarely preserve omphacite and other high-pressure minerals. These data are integrated with LA-ICP-MS U–Pb zircon dating, which reveals REE profiles indicative of crystallization under igneous to high-pressure metamorphic conditions. The eclogite protoliths display distinct geochemical affinities—sometimes of oceanic origin—and emplacement ages ranging from the Late Cambrian to the Silurian. Moreover, the prograde metamorphic evolution from prehnite-pumpellyite to eclogite facies is recorded by low-grade mineral inclusions within the cores of eclogitic garnet. Petrological modeling and zircon–rutile Ti–Zr thermometry consistently indicate peak eclogite-facies conditions. The prograde path, transitioning from very low- to high-pressure conditions with a temperature–depth ratio of ≤10 °C/km, suggests that these rocks were deformed and metamorphosed during oceanic subduction followed by continental collision.

Orogenic Growth and Erosion in a Subduction orogen: Insight from the Albanides-Hellenides

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Keywords: Albanides-Hellenides, underplating, exhumation.

Crustal underplating has been described as a key mechanism of accretion in several orogens of the Alpine-Himalayan belt. This process promotes crustal thickening in subduction orogens by scraping slices of continental lithosphere from the downgoing plate. Although geophysical data provide valuable insights into the deep structure of these orogens, the dynamics of deep crustal underplating and its surface expression remain poorly understood. The Albanides-Hellenides in the central-eastern Mediterranean provide a compelling case to investigate the dynamics of these processes and their impact on exhumation patterns. The Albanides-Hellenides evolved through the accretion of continental material during the eastward subduction of Adria beneath Eurasia since the Late Cretaceous (Burchfiel et al., 2018; Robertson & Shallo, 2000). The thickening at depth occurred along with the development of a shallow fold-and-thrust belt, characterized by deformation styles controlled by the thickness of the décollement level, represented by Triassic evaporites (Mazzoli et al., 2022; Roure et al., 2004). The present study investigates recent crustal thickening in the Albanides-Hellenides by integrating new and existing low-temperature thermochronological data, tectono-stratigraphic analysis, and modeling to explore the relationship between deep-seated structures and surface deformation. Our results reveal a pulse of exhumation orogenic front during the middle/late Miocene to Pliocene, amounting to approximately 3–4 km, which we propose has been driven by a deep-seated thrust system. In the hinterland, extension-related exhumation progressively rejuvenated toward the west, from middle Miocene to Pliocene, suggesting slab rollback as geodynamic driver. These findings provide insights into the timing and kinematics of subduction-related orogenic processes. They demonstrate that, from the middle Miocene to the Pliocene, crustal accretion through deep-seated structures occurred at the same time as hinterland extension driven by slab rollback. This tectonic phase likely marks the most recent stage of a long-term accretionary cycle that has driven orogenic growth by accreting slices of continental crust, contributing to significant crustal thickening in an orogen with retreating subduction boundaries and suggest a general plate reorganization in the Mediterranean during the Miocene.

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From crust to mantle: constraints on strength-controlled deformation in the European eastern Southern Alps from analogue models

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Keywords: analogue modelling, inversion tectonics, mechanical and structural inheritance.

In convergent settings, mechanically strong lithospheric blocks ("indenters") transmit shortening into adjacent weaker plates. Within the Cenozoic Alpine orogeny, the Adriatic continental upper plate acts as such an indenter. 3-D gravity and thermal modelling (Spooner et al., 2019) and strength calculations (Willingshofer & Cloetingh, 2003) indicate that the Adriatic lithosphere is colder, denser and hence stronger than the European plate, yet it hosts lateral rheological contrasts inherited from Permian magmatism and Jurassic platform–basin segmentation. These inherited contrasts probably influenced Miocene SE-vergent inversion in the eastern Southern Alps (ESA). Building on recent crustal-scale analogue work (Sieberer et al., 2023, 2025), we use new lithospheric-scale experiments to investigate how such heterogeneities control crust–mantle coupling and surface uplift.

Unlike earlier lithospheric analogue studies that targeted shortening of weak orogenic wedges at plate boundaries, our six experiments (1 cm ≈ 30 km; 0.5–1 cm h^{-1} ≈ 1.2–2.3 cm a^{-1}) focus on internal deformation of the indenter itself. Each model comprises a three-layer stratification: brittle upper crust, ductile lower crust and ductile lithospheric mantle. Mantle-layer thickness is constant, whereas the brittle- and lower-crustal thicknesses vary to impose inherited strength contrasts parallel to convergence. The brittle crust is a mixture of dry feldspar and plastic sand; the ductile layers are PDMS–Al_2O_3–plasticine blends calibrated to a comparatively "weak" lower crust above a stronger mantle lithosphere. A moving indenter supplies convergence.

Shortening is partitioned vertically and laterally in response to imposed strength gradients. Where the brittle crust is thick, weak lower crust is squeezed sideways and thins, creating an inverse brittle- versus ductile-crust thickness relationship and localising deformation into narrow, high-strain belts. This redistribution of viscous lower crust triggers large wavelength folding of the mantle lithosphere that remains kinematically linked to upper-plate structures, demonstrating strong crust–mantle coupling. Thrust nucleation occurs in each of the six models by ~5 % bulk shortening, yet lithospheres with higher overall strength and stronger lateral contrasts evolve faster: they develop closely spaced thrust sheets, achieve higher mean shortening rates and reach peak surface uplift earlier than weaker configurations, which continue to rise while mantle folding and lower-crustal flow proceed.

The experiments show how inherited lateral strength variations within an otherwise strong indenter modulate crust–mantle coupling, deformation style and uplift history. The experiments provide a quantitative framework that links deep lithospheric processes to observable crustal structures and topographic evolution in the ESA and can guide interpretation of deformation in other convergent zones with heterogeneous continental lithospheres.

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From Variscan to Alpine tectonics: the complex tectonic history of the Argentera Massif unravelled by multidisciplinary investigation

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Keywords: Argentera Massif, structural analysis, shear zone.

Shear zones have a primary influence on the geometry and evolution of orogenic belts and assessing their role is crucial to reconstruct the tectonometamorphic evolution of orogens. Such structures commonly record a complex and polyphase deformation history and, in investigations at a regional scale, it is essential to recognize their evolution. This is difficult because shear zones characterized by similar rocks and kinematics may have originated at very different times and for very different causes. Fieldwork, integrated with several techniques for microstructural and geochronological analyses, is recommended in the study of shear zones aimed at unravelling regional-scale tectonic evolution of orogens.

The Argentera Massif, located in the Western Alps, recorded a log tectonic history from Variscan to Alpine orogeny and is characterized by the presence of many regional-scale shear zones with complex evolution. Therefore, it offers the perfect case study to show how to approach the investigation of crystalline basement that underwent a long deformation history occurred in very different contexts and time.

Most of the Alpine deformation in the Argentera Massif is concentrated along low-grade ductile, brittle-ductile and brittle shear zones. Low-grade mylonitic and ultramylonitic schists present a deformation age of ~22 ($^{40}Ar/^{39}Ar$ on phengites; Sanchez et al., 2011). A reactivation of the Variscan Ferriere-Mollières shear zone (FMSZ) coupled with the formation of new structures (Fremamorta shear zone, Bersezio Fault) has been hypothesized. Several E-W oriented alpine shear zones with a reverse top-to-the-S sense of shear are are also present and they were mapped for the first time by Carosi et al. (2016). The detailed structural and geochronological study of the FMSZ shear zone revealed that variscan teranspressional deformation is still well preserved and a complex evolution under decreasing temperature from amphibolite facies down to greenschist facies conditions was recognized (Simonetti et al., 2021). The lower grade rocks of the FMSZ are highly sheared ultramylonites gradually passing to higher grade less sheared rocks (dated between ~340-330 Ma ~320 Ma, U-Th-Pb on monazite) along a continuous deformation gradient without crosscutting relationship. Therefore, the assumption that low-grade deformed rocks were only produced during the alpine event is not always verified. The main alpine structures represent first-order shear zone and the newly recognized shear zones are second- and third-order structures that further accommodate the nearly N-S shortening recognized during the early Miocene.

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Early Alpine subduction (67 Ma) and plate-interface accretion of oceanic lithospheric mantle (Erro Tobbio Massif, Italy)

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Keywords: eclogite, subduction, chronology.

Understanding the distribution and evolution of serpentinized mantle in subduction zones is crucial for unraveling tectonic and rheological processes, and for tracking the fate of water during subduction. A key question remains whether serpentinization occurs predominantly in the subducting slab or the overlying mantle wedge, and when slab-derived rocks are accreted to the plate interface. These issues are central to interpreting the dynamic evolution of both fossil and active subduction systems.

In this study, we present new geochronological data from oceanic metagabbro and rodingite hosted within serpentinized peridotites of the Erro-Tobbio unit (Western Ligurian Alps). These rocks record early eclogitization ages at ~67 Ma, significantly older than the subduction ages (50–38 Ma) reported so far for ophiolitic eclogites and serpentinites in the same region and across the Western Alps. Our findings indicate that the Erro-Tobbio unit was subducted and accreted to the subduction hanging wall well before other high-pressure rocks now exposed in the Alps. This implies that the unit remained in a subduction zone setting for at least 17 million years prior to the arrival of younger subducted materials.

We propose that the metaophiolites currently exposed in the Alps were originally located near the paleo-continental margins of Africa and Europe and were involved in early stages of continental collision. The oceanic lithosphere subducted between 67 and 50 Ma likely continued its descent into the mantle. Additionally, we suggest that the close association of serpentinized oceanic lithosphere with continental fragments played a critical role in enhancing the buoyant exhumation of high-pressure rocks, contributing to their present exposure in the Alpine belt.

The Variscan non-conformity in the SE Ötztal-Stubai Complex (Austroalpine Domain, Eastern Alps, N-Italy)

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Keywords: Eastern Alps, Alpine metamorphism, Variscan non-conformity.

The Ötztal-Stubai Complex, the largest unit of the Austroalpine domain, consists of a polymetamorphic basement and its autochthonous Permian-Mesozoic metasedimentary cover, made by a metaconglomerate (*Basal Conglomerate or Alpine Verrucano*), calcareous schists and marbles, referred all together in the literature as the *Brenner Mesozoikum*. These units have been interpreted to represent the lower to medium grade metamorphic equivalent of the Upper Carboniferous to Anisian succession of the former passive Austroalpine margin, resting on the polydeformed and polymetamorphic Ötztal basement. In the San Martin am Schneeberg and Tribulaun areas (South Tyrol, NE Italy) the basement-cover non-conformity surface is still largely preserved. Structural investigations across such discontinuity served to reconstruct the Alpine deformative and metamorphic history not only in the metasedimentary cover, but also within the polymetamorphic Ötztal basement. The occurrence of mafic to intermediate dikes of presumed Permian age that crosscut the regional foliation in the basement but do not intrude the post-Variscan cover, served as an additional marker in the discrimination of Alpine and pre-Alpine structures and mineral assemblages in the Ötztal basement. Alpine deformation resulted in a penetrative foliation in the sedimentary cover coupled with a stretching lineation due to a top-to-W (NW) shearing. Dikes just below the non-conformity appear to have bee sheared, displaying a well developed S-L tectonic fabric, whereas moving away from the surface, dikes appear to be statically recrystallized P-T estimates by conventional geothermobarometry and forward thermodynamic modelling constrain metamorphism of Alpine age in metaconglomerates and dikes at 450-500°C and 0.8-1.0 GPa. ^{40}Ar-^{39}Ar dating of micas within conglomerates and recrystallized biotite in dikes provide ages of 85-95 Ma. These data are very close to the age of the eclogitic metamorphism in the Texel unit and the HP amphibolite facies metamorphism in the Schneeberg complex. All together these data suggest that metamorphic peak conditions were experienced contemporaneously by the three units when they were at different crustal levels. During exhumation, the HP Texel unit was first coupled with the Schneeberg unit (the two units show a common evolution since the amphibolite facies re-equilibration of the Texel eclogites) and then the Schneeberg-Texel was brought in contact with the Ötztal basement and cover at shallow crustal level.

Late Cretaceous pre-collisional evolution of the retrobelt of the Southern Alps (N Italy): insights from *in-situ* U-Pb carbonate dating of major tectonic structures

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Keywords: U-Pb dating, Southern Alps, tectonics.

The formation of the Alps is traditionally linked to the collision between Europe and Adria from the middle-late Eocene. However, evidence of Late Cretaceous high-pressure metamorphism in the Austroalpine units and fault activity along major structures of the Southern Alps (e.g., the Orobic Thrust) reveals that deformation began well before the main collisional phase, affecting both the north- and south-verging sectors of the orogen. While most nappe-stacking and deformation occurred north of the Periadriatic Fault, early crustal shortening was also affecting the S-verging retro-belt, forming a several-hundred-kilometre-long, E-W trending fold-and-thrust belt.

Pre-Eocene thrusting in the Southern Alps is evidenced by middle-late Eocene magmatic bodies that cut across major tectonic structures, and by Upper Cretaceous foredeep sediments derived from the erosion of the Variscan basement. These findings suggest that the Southalpine chain was already structured well before the onset of the Alpine collision.

Despite this, the pre-collisional evolution of the Southern Alps remains poorly constrained due to the lack of absolute dating, as key structures involve the Triassic–Cretaceous carbonate sequence. Herein, U-Pb dating of calcite tectonites (i.e., calc-mylonites, growth fibres and veins) from major South-verging thrusts in the central Southern Alps, reveals Late Cretaceous ages, confirming early deformation in the Southalpine domain. These ages suggest a not in-sequence pattern for fault activity and multiple reactivation phases across both internal and external parts of the belt. Stable isotope analysis (O-C) of carbonates indicates the involvement of distinct paleo-fluids during different reactivation events.

This multidisciplinary study demonstrates that S-SE-directed thrusting and folding began in the Southern Alps already during the Late Cretaceous, predating the onset of Alpine collision, and highlights the recurrent reactivation of these major structures throughout the Alpine orogen evolution.

The transition from a thickened to thinned lower continental crust, as detailed in structural inhomogeneities recorded in the Valpelline Unit fragment of the Adria margin in the Western Alps

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Keywords: deep to Lower crust, structural features, homogeneities.

The lower continental crust is a unique environment for the onset of fundamental geodynamic processes, including the transition from thickening to extension, delamination, crustal melting, recycling, and growth. Although the locus of such fundamental processes for the Earth's plate tectonics, its structure, and composition are known only from indirect observations, xenoliths, and several crustal sections worldwide, the latter used as paradigmatic examples.

In this contribution, we analyse the structural evolution of the Valpelline Unit (Series) in the Western Alps (Dent-Blanche Nappe, Austroalpine domain) and its influence on the evolution of the composition and inhomogeneities of the lower continental crust. We will discuss the structural features related to the transition from a thickened crust, a consequence of an orogenic cycle, to incipient lithospheric extensional tectonics promoted at deep levels of the crust.

A progressive deformation characterises the Valpelline Unit, where high-pressure granulite associations are progressively replaced by low-pressure features developed during diffuse melt production in metapelites, and to a lesser extent, in metabasites. Meso- and micro-structural analysis, combined with thermodynamic modelling and P-T estimates, geochronology and numerical modelling, allowed the reconstruction of a geodynamic model where a thickened continental crust evolved to a thinned crust during an extensive partial melting process where the distribution of the typical lithologies of the lower crust are widespread and tectonically arranged to produce an higly dismebered-boudinaged-inhomogeneous lower crustal distribution.

S15

Biotic and Sedimentary Dynamics Through Time: Climate, Carbonates, and Beyond

Conveners and Chairpersons

Claudia Agnini (Università di Padova)

Gabriele Gambacorta (Università di Firenze)

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The Athesian Volcanic District (upper Cisuralian, Southern Alps): Palynostratigraphical implications

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Keywords: palynology, Paleozoic, biostratigraphy.

The Athesian Volcanic District (AVD) is one of the largest and best preserved Cisuralian volcanic successions in Europe. Geological mapping and zircon radiometric dating allow to reconstruct the volcanic activity with an exceptionally high chronostratigraphic resolution. The continental sedimentary sequences intercalated between the volcanic units were deposited during phases of low volcanic activity and were usually associated to alluvial-lacustrine environments. In addition to other fossil remains, they yielded abundant and diverse palynological associations. Ten stratigraphic successions belonging to the Monte Luco, Verano, Guncina, and Tregiovo formations have been studied. They are middle–upper Kungurian in age, according to radiometric datings, and were collected along the outcrops of 1) Kleiner Laugen/Monte Luco Piccolo, 2) Sinich/Sinigo, 3) Vöran/Verano, 4) Ums/Umes, 5) Grissian/Grissiano, 6) Gorl, 7) Nopp, 8) Sankt Jakob/San Giacomo, 9) Tregiovo Village, and 10) Oberbozen/Soprabolzano. The study of these associations allows us to calibrate the stratigraphic ranges of key Permian palynological taxa such as *Falcisporites stabilis*, *Gigantosporites aletoides*, *Lueckisporites virkkiae*, *Nuskoisporites dulhuntyi*, and *Taeniaesporites noviaulensis*. The presence of these taxa in the Athesian Volcanic Group, often used as markers for the Guadalupian or even Lopingian, has implications for their chronostratigraphic distribution with earlier occurrences in the late Cisuralian, at least in the SE part of the Euramerican phytoprovince.

Stasis and changes in sedimentary successions: punctuated equilibria in stratigraphy?

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Keywords: stratigraphic boundares, environmental changes, depositional systems.

Sedimentary successions are characterized by irregular superposition of different rocks and rock associations, commonly grouped in lithostratigraphic units. The persistence of the same rocks or rock associations for a certain period of time ends when new sedimentary rocks appear, documenting changes in the factors controlling sedimentation, marking the boundaries of lithostratigraphic units. These boundaries may be related to discontinuities and gaps in the sedimentation, but frequently lithological changes between periods of homogeneous sedimentation document rapid changes without gaps. In this case, the vertical transition between lithostratigraphic units documents geologically rapid environmental changes that results from the rapid transition from one to another depositional environment. As a consequence, the study of thick, stratigraphically continuous sedimentary successions shows periods of stable sedimentation followed by more or less rapid changes, marking the transition from different lithostratigraphic units.

Rapid lithological changes not associated with gaps in sedimentation may be ascribed to three major causes: tectonic control (such as rapid increase in subsidence), plate movement across climate belts or major climate changes. As a consequence, the gradual transition predicted by the Walther's law, that can be appreciated laterally, results to be more rapid across time: in general, lateral transition are more gradual than the vertical ones.

Chronostratigraphic units, originally defined on the base of the fossil contents (such as ammonoids in the Triassic), frequently match with major lithostratigraphic turning points, suggesting a correlation between major environmental changes and speciation. The causal origin of this possible correlation needs to be investigated: the stratigraphic record documents time interval characterized by stable depositional conditions (stasis) followed by rapid lithological changes that in some cases are associated with extinction or speciation. This observation mirrors the punctuated equilibria model, suggested for biotic evolution: a more detailed correlation between evolutionary steps and major lithological changes could be useful to verify a causal relationship between environmental changes that may promote allopatric evolution and the extinction and rapid appearance of new species. In detail, it is necessary to understand the possible causes of rapid lithological changes in continuous succession, separating the contribution of tectonics, climate changes and plates drift: the identification of lithostratigraphic boundaries controlled by major climate changes and the evaluation of the way this changes affected the stratigraphic evolution of sedimentary successions is critical to shed lights on the effects that the rapid climate changes we are experiencing today may have on depositional environments.

Coccolithophores and East Asian Monsoon variations during the Last Interglacial (MIS 5e) in the South China Sea: a possible analogue for future climate change?

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Keywords: coccolithophores, marine isotope stage 5e, East Asian Monsoon.

Since the late 19th century, the rise in global mean temperatures and atmospheric carbon dioxide (CO_2), primarily driven by anthropogenic activities, has made the need to predict ocean response to climate change increasingly pressing.

Marine Isotope Stage 5e (MIS 5e, ~130-116 kyr) is a past interglacial interval that, despite presenting some differences from the current warming, offers important insights into the evolution of the current climate and its natural forcings. Hence, studying MIS 5e could be crucial for deepening our understanding of biotic responses to future climate change.

Coccolithophores, calcifying marine microalgae particularly sensitive to environmental changes, represent an excellent tool to investigate past climate variations. Analyzing their fossil remains in deep-sea sediments provides valuable insights into their role in the carbon (C) and carbonate systems over time.

In this study, we analyze the fossil coccolithophore assemblages from International Ocean Discovery Program (IODP) Site U1501 from the South China Sea during MIS 6-MIS 3 interval (~158-50 kyr), to document their responses in terms of abundance, assemblage composition, and contribution to $CaCO_3$ production during the deglaciation phase (Termination II) and the last interglacial.

At the studied site, coccolithophores tracked variations in sea surface temperatures (SSTs) and East Asian Monsoon (EAM), with the latter causing shifts in water column stratification and nutrient availability. During glacial intervals lower abundances are related to low SSTs and enhanced EAM, which determines increased water column mixing and productivity. Coccolithophore abundance increases during T-II in response to SSTs rising, and it remains high along the entire MIS 5e, marked by more stratified and warm-water conditions due to a weakened EAM. Coccolithophores contribution to $CaCO_3$ also increased during T-II and MIS 5e, mainly due to higher abundances of the dominant species *Florisphaera profunda* (up to 83% of the entire assemblage), along with less abundant heavily calcified taxa such as *Gephyrocapsa oceanica* medium and *Helicosphaera carteri*.

These results underscore the importance of coccolithophores in climate reconstructions and of considering both dominant and less abundant but highly calcified species in oceanic C cycle reconstructions. Furthermore, this work shows similarities with future EAM scenarios predicting a decrease in total primary productivity, a weakening of the monsoon gyre, and southwestward retreat of the monsoon trough (Dao & Yu, 2022; IPCC, 2023). It highlights not only the relevance of the past as a key to understanding future climate change, but also the crucial role of coccolithophores in the global carbon cycle.

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Changing in the accommodation space according to Luis Pomar and insight for the sedimentary record: two examples from the Mediterranean Sea

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Keywords: Pomar, accommodation space, carbonate ramp.

A key Pomar's concept is the ecological accommodation space. According to Luis in the carbonate systems the base level for sediment accumulation, although influenced by hydrodynamics, is also strongly controlled by ecological factors. Consequently the original definition, "the space available for sediment accumulation" was extended in subdividing into "physical" and "ecologic" accommodation. The ecological accommodation refers to the space available for carbonate biota accumulation, which, in addition to hydrodynamic conditions, is strongly influenced by the ability of organisms to produce and accumulate sediments beyond the hydrodynamic thresholds characteristic of clastic systems. The classical example is represented by the evolution from a carbonate ramp to rimmed shelf in the Upper Miocene of Balearic Islands. The change from a ramp to a rimmed shelf resulted from the replacement of a system with a physically dominated base level, which was dependent on a loose-grain-producing biota, by a system with a biologically dominated base level, which was characterized by an euphotic, framework- producing biota. An application of change in the accommodation space can be observed in the Cenozoic carbonate platform of the Central Mediterranean. From the late Paleocene to the Early Miocene, the Latium-Abruzzi carbonate platform (Central Apennines) functioned as a shaved, isolated platform exposed to wave action in the middle of the proto-Mediterranean region. During transgressive and highstand sea-level phases, bioclastic sediment accumulated, whereas, in the subsequent falling and lowstand stages, wave abrasion eroded the seafloor, redistributing the sediment. In the early Burdigalian, as the Mediterranean progressively evolved into a semi-enclosed sea due to the initial closure of the Indo-Pacific connection, the reduced wave-base depth characteristic of enclosed basins increased accommodation space. This shift facilitated sediment accumulation, leading to the development of a complete inner-to-outer ramp facies belt within the Miocene Latium-Abruzzi ramp. A similar process occurred in the Apulia Carbonate Platform, located east of the Latium-Abruzzi platform. During the Paleogene, sediment eroded from the platform infilled the adjacent basin, establishing a carbonate ramp over the older basin deposits. In this setting, cross-bedded carbonates accumulated in middle to outer ramp environments, while the inner ramp remained within the zone of wave abrasion. As a result, sediment generated in the inner ramp was transported to the middle and outer ramp settings. It was only during the early Messinian, when wave-base depth decreased in the proto-Adriatic basin that increased accommodation space allowed for the development of a complete inner-to-outer ramp facies belt. In both cases, paleogeographical changes during the Miocene led to the development of small restricted basins in the Mediterranean region, producing a change in the accommodation space.

Carbonate platform dynamics across the Cenomanian/Turonian Boundary: the OAE2 record in the Akrabou Formation (Southeastern Morocco)

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Keywords: Cenomanian/Turonian boundary, OAE2, Moroccan North Saharian Platform.

During Early Cretaceous, most of North Africa was characterized by continental sedimentation. It was at the Cenomanian/Turonian Boundary (early Late Cretaceous), that an important eustatic sea level rise led to the flooding of a huge portion of continental margin, from Egypt to Morocco, with the emplacement of an epicontinental carbonate platform known as North Saharian Platform. The Cenomanian/Turonian Boundary corresponds to one of the warmest periods in Earth history, highest sea level stands, and an important oceanic anoxic event (OAE2). Our research focuses on Southeastern Morocco, between the Central High Atlas and Anti-Atlas ranges, where the Akrabou Formation (Ferrandini et al., 1985) records this important event.

The Akrabou Formation, up to 100 m thick, reveals a dynamic depositional history. Its lower portion is characterized by low-energy, shallow-water environments, testified by fine-grained wackestone/packstone with abundant micrite, very small oligotypic benthic foraminifera, ostracods, bivalves, and echinoderms; oyster-rich beds alternate with fine limestones. Upwards, the succession changes to laminated lime-mudstones with planktonic foraminifera, chert lenses, and ammonite-bearing nodules, indicating a deepening. Subsequently, a shallowing trend is marked by fine-grained packstone/wackestone with an oligotypic assemblage of small benthic foraminifera, echinoderms, bivalves and macroforaminifera, with chert and ferruginous surfaces in interbeds. Abundant micrite suggests the return to low energy shallow-water environments. An increase in energy is observed upward with coarser, cross bedded levels. On top, peritidal facies mark the emersion of the platform and the re-establishment of continental clastic sedimentation.

Stable isotope analysis ($\delta^{13}C$ and $\delta^{18}O$) on bulk carbonates and oyster shells reveals a distinct $\delta^{13}C$ positive broad peak of +3‰ VPDB, aligning with OAE2 values worldwide (Voigt et al., 2008). Highest $\delta^{13}C$ values occur in the lower portion of the platform, and then decrease to around -2‰ VPDB, coinciding with a thinly stratified interval interpreted as the maximum flooding phase.

OAE2 significantly stressed the epicontinental platform, as suggested by the temporary shift to deeper environments. However, this crisis was transient and the shallow benthic carbonate community was quickly reestablished. As observed by Wang et al. (2021), the maximum retreat of the platform, and hence the peak of its crisis, is not coincident with the stable isotopic record of OAE2, but rather occurs with a significant delay.

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Where did all the carbonate go? Swinging modes of carbonate production at the Carnian Pluvial Episode (Late Triassic)

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Keywords: carbonates, diagenesis, Triassic.

The Carnian Pluvial Episode (CPE) is a sharp climatic perturbation that occurred in the Late Triassic, ca. 234-232 Ma. It was most likely triggered by the eruptions of the Wrangellia Large Igneous Province and had a significant impact on biota and marine ecosystems.

The crisis of shallow water carbonate depositional systems stands out as one of the most severe effects of the CPE. In the Southern Alps of Italy, the growth of high-relief carbonate platforms, mostly built by microbialites, was suddenly halted; a switch from microbial to skeletal carbonate production is observed Tethys-wide. At approximately the same time, calcareous nannofossils appear worldwide in deep marine facies (Dal Corso et al., 2020).

The crisis of carbonate depositional systems was investigated in a succession located near Misurina (central Dolomites, northern Italy), with the aim of identifying what type of carbonate production replaced the early Carnian shallow microbial platforms. Three land sections were logged and sampled, and a ca. 100 m long continuous core was drilled, which together cover ca. 300 m of prevailing clayey marlstones to limestones. The first pulses of the CPE were identified in the lower part of the core interval.

Carbonate occurs in three distinct intervals: a lower calciturbiditic, a middle marly and an upper limestone-marl interval. In the basal interval, carbonate grains—rich in microbial components and in photosynthesizing organisms as green algae and calcimicrobes—were shed from nearby platforms. Calciturbidites disappear shortly after the first geochemical signals of the CPE. Calcareous nannofossils (*Orthopithonella* spp.) occur in the upper calciturbiditic interval, and persist throughout the marly interval. The marly interval still contains carbonate, mostly as fine-grained particles and marine to early burial cements. In the limestone-marl interval, skeletal components (mollusks, corals, echinoderms, green algae and foraminifers) are the dominant producers.

In summary, at Misurina, changes in carbonate components show an unexpectedly complex pattern. The mixed microbial-skeletal composition of calciturbidites contrasts with that of other pre-CPE records, and suggests that the transition from microbial to skeletal carbonate production may have begun before the main CPE event. Coexistence of microbial-skeletal calciturbidites and calcareous nannofossils suggests that pelagic carbonate production did not simply replace microbial carbonate production on platforms. Finally, there is a time interval after the demise of high-relief microbial platforms, but before the emplacement of skeletal ramps, without productive shallow carbonate depositional systems. Fine-grained carbonate was still produced, which nature however remains to be understood.

Dal Corso J. et al. (2020) - Extinction and dawn of the modern World in the Carnian. Science Advances, 6(38), eaba0099, https://doi.org/10.1126/sciadv.aba0099.

The Pelsa/Vazzoler Fossil-Lagerstätte: a window into the Middle Triassic biodiversity of the paleotropics

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Keywords: Mesozoic marine revolution, Triassic radiation, Dolomites.

The Dolomites (NE-Italy) are one of the most extensively studied mountains in the world, especially for their Triassic carbonate platforms and coeval basinal sequences. The newly discovered Pelsa/Vazzoler Fossil-Lagerstätte (Agordo Dolomites, Belluno) yielded a remarkably diversified fossil assemblage of late Ladinian age, deposited in a small intraplatform basin.

It includes thousands of well-preserved silicified invertebrates belonging to more than 100 molluscs species and dozens of echinoderm, brachiopod, cnidarian, and porifera taxa. Studies on benthic molluscs suggest that this Lagerstätte, in the Sciliar Formation, yields a structure comparable to the famous lower Carnian San Cassiano Lagerstätte and put forward that molluscs' radiation may have occurred as early as the late Middle Triassic. In this fauna, associated with small, isolated patch reefs in a tropical climate, epifaunal filter-feeding bivalves adopted new antipredatory features. Additionally, small-sized gastropods conquered new ecospaces, including parasitism and microcarnivory on sponges and scleractinian corals. This silicified fauna confirms that the diversity of the modern type recognized in the San Cassiano Lagerstätte has older, late Ladinian roots. Thus, it further indicates that the upper Middle Triassic adaptive radiation was likely biotically driven, rather than constrained mainly by abiotic factors. Indeed, this event precedes by 6–7 myr the Carnian Pluvial Episode and appears not to be connected to a major climate change.

Furthermore, over 250 fish specimens were found which belong to at least 10 species, including miniature ray-finned fishes like *Habroichthys* and *Marcopoloichthys*, the flying fish *Thoracopterus wushaensis*, previously described from China, but also coelacanths and sharks. This makes the Pelsa/Vazzoler Fossil-Lagerstätte the most diverse vertebrate fossil deposit in the Dolomites. Abundant conifer, fern, and cycad remains, together with rare insects, help to reconstruct the surrounding terrestrial environment. Finally, ammonoids, conodonts, and radiolarians provide a biostratigraphic framework and insights into extraplatform basin faunas beyond the carbonate build-up. Together, the Pelsa/Vazzoler Fossil-Lagerstätte is promising to provide further and new insights into the biodiversity of the western Tethys tropical ecosystem during the late Ladinian.

Depositional environments of the Ladinian Pelsa - Vazzoler Basin

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Keywords: isotope, Ladinian, Dolomites.

Mt. Pelsa is a relief located near the town of Agordo (BL) in the Dolomites. Most of the mountain consists of a Ladinian (Middle Triassic) carbonate platform that experienced a tectono-magmatic event leading to the formation of an intraplatform basin, the so-called Pelsa – Vazzoler Basin. Successively, that event led to the death of many Ladinian carbonate platforms in the Dolomites area. The stratigraphic sequence of the Pelsa – Vazzoler Basin comprises an alternation of slightly dolomitized lime-mudstone, marl, and volcanic ash layers, deposited in an environment which may have temporary reached euxinic conditions. This locality is renowned because of the preservation of a highly diversified fossil biota, primarily composed of plants, invertebrates, and fishes. Ammonite biostratigraphy has allowed to date the sequence to the *A. neumayri* Sbz (Longobardian).

Preliminary studies of the ichthyofauna have revealed that it shows many similarities with other important Middle Triassic fish assemblages from both ends of the Tethys Ocean (e.g., Monte S. Giorgio fauna in Lombardy and Switzerland, and Xingyi fauna in Southern China). Moreover, the benthic fauna, mainly represented by molluscs and gastropods, but also corals, brachiopods being scarcer, sponges, and echinoderms, underwent a complete substitution by silica, one of the first recorded since the P-T mass extinction.

Despite the impressive paleontological interest , there is still a lack of research about the paleoenvironment of the basin; the studies of the feature of the sequence, during the fieldwork, led us to theorize that the Pelsa-Vazzoler basin was a intraplatform basin where the subsidence were controlled by syn-sedimentary faults (breccias) and the sedimentation was controlled by slumps from the edge of the basin (load cast structure and chaotic transport of fossils remains that successively were substituted in silica). In this work, we present the result of facies analysis and the first result of geochemical analyses from the older part of the basin and around the fossil fish horizon ($\delta^{13}C$, $\delta^{18}O$ and TOC), thin sections analyses (diagenesis events) , which contribute to a better description of the depositional environments in the Pelsa - Vazzoler Basin.

Calcareous nannofossil paleoceanography of Cretaceous Oceanic Anoxic Event 3: from local to global perturbations

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Keywords: Oceanic Anoxic Event 3, calcareous nannofossils, paleoceanography.

This study revises calcareous nannofossil biostratigraphy across the Coniacian-Santonian Oceanic Anoxic Event 3 (OAE3), sharpening supra-regional correlations, enhancing precision in dating and paleoenvironmental reconstructions.

Quantitative analyses of nannofossil assemblages of sites in the eaquatorial and south Atlantic Ocean as well as Indian Ocean provided insights into paleoecological and paleoceanographic conditions during OAE3. The temperature index (TI) indicates overall warm conditions, though brief cooling events occurred in the Coniacian-early Santonian, followed by a more sustained cooling trend in the middle Santonian. The nutrient index (NI) revealed that trophic conditions during OAE3 were mostly local, with nutrient-rich conditions limited to upwelling zones and areas receiving enhanced runoff, rather than reflecting a global fertilization episode.

All literature data available for *Micula* and *Marthasterite*s abundance were integrated to obtain a large -scale picture across OAE3: the abundance peaks are synchronous and cannot be preservation artifact or local signals , thus implying imply large scale perturbations of oceanic surface waters during short time intervals. Two acmes of *M. furcatus* were identified, with the most significant peak at the onset of OAE3, indicating a deep nutricline in oligotrophic surface waters. Five acmes of *M. staurophora* were recognized, with a climax during the latest Coniacian-early Santonian, likely linked to extreme ocean stratification. These acmes also serve as biostratigraphic markers, improving the resolution of Late Cretaceous boundaries, implementing the resolution of the Turonian/Coniacian, Coniacian/Santonian, and Santonian/Campanian.

Planktic foraminiferal response to the Early Eocene Climatic Optimum (EECO): abundance shifts, size changes, and $\delta^{13}C$ signals

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Keywords: planktic foraminifera, Early Eocene, biotic response.

Planktic foraminifera are important indicators of paleoceanographic and climatic conditions due to their high sensitivity to environmental changes such as temperature, pH, nutrient availability, and oxygenation. The Early Eocene Climatic Optimum (EECO, ~53–49 Ma), the warmest long-term interval of the Cenozoic, provides a unique framework to evaluate ecosystem resilience and evolutionary dynamics under sustained global warming (Westerhold et al., 2018). This study integrates relative abundances, test size, and stable isotope data from Atlantic, Pacific, and Indian Ocean records to assess the ecological and evolutionary responses of planktic foraminifera to the EECO. We reveal significant modifications in planktic foraminiferal assemblages during two major hyperthermals of the EECO, the J event (53.26 Ma), which marks the beginning of the EECO, and the K/X event (52.86 Ma).

A global reorganization of surface-dwelling communities is observed: the symbiont-bearing genus *Morozovella* experienced a marked and permanent decline in abundance and diversity, while *Acarinina* globally dominates the assemblage. These trends likely reflect differing adaptive strategies to environmental stress. While *Morozovella* maintained its position in the mixed-layer and increased in size, *Acarinina* shows smaller test sizes and lower $\delta^{13}C$ values, suggesting a deepening in the water column and slightly reducing photosymbiosis to evade the heat (Filippi et al., 2025). The changes in the assemblage were accompanied by morphological and ecological shifts. A global switch in *Morozovella* coiling direction (dextral to sinistral) occurred close to the K/X event (Luciani et al., 2021), potentially reflecting cryptic speciation and selective survival of more adaptable sinistral morphotypes. Simultaneously, the virtual disappearance of *Chiloguembelina* indicates a contraction of oxygen deficient zone, in agreement with nitrogen isotope data showing enhanced ventilation (Auderset et al., 2022).

The recorded shifts in assemblage composition of this study demonstrate that EECO events acted as turning points, driving planktic foraminiferal communities into new configurations from which they never fully recovered, indicating a loss of long-term ecological resilience. The relatively gradual pacing of EECO warming contrasts sharply with the rapid anthropogenic warming of today. Our findings underscore that even slow climatic perturbations can induce lasting and irreversible ecosystem changes, highlighting the potential for more severe and immediate consequences under modern rates of climate change. These deep-time scenario provide critical insights into the mechanisms and limits of marine ecosystem resilience.

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Late Cretaceous tectono-stratigraphic evolution of the northern margin of the Apulia Platform: insights from the Orfento Formation (Maiella Mountain, central Apennines)

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Keywords: Upper Cretaceous, Apulia carbonate platform, synsedimentary tectonics.

The Orfento Formation is an Upper Cretaceous bioclastic unit developed along the northern margin of the Apulia Platform, magnificently exposed in the Maiella Mountains. Despite extensive research on this unit since the 1960s, its depositional history is still debated (Eberli et al., 2019). In this study, the complex depositional architecture of the Formation has been investigated along the seismic-scale outcrop of Pennapiedimonte, highlighting a depositional model controlled by the interplay between rudist-rich bioclastic sedimentation, the morphology of the margin, and extensional tectonics. Panoramic photomosaics, a three-dimensional virtual outcrop model (VOM), and eight detailed stratigraphic logs, distributed across the entire outcrop, allowed the detailed subdivision of the Orfento Formation into seven intervals characterized by distinct stratigraphic stacking patterns. The overall vertical facies variation shows a transition from fine-grained wackestone–packstone dominated intervals (1 to 3), containing planktonic foraminifera, to coarse-grained packstone–grainstone dominated intervals (4 to 7), locally containing well-preserved rudists in growth position. The correlation of the intervals reveals significant facies and thickness variations across two NNW–SSE normal faults, approximately parallel to the outcrop, both dipping to the WSW. In particular, thickness changes are abrupt along the fault dip direction, with variations up to 25 meters, accompanied by wedge-shaped and onlap geometries observable in outcrop. In contrast, changes along the fault strike direction are gentler, with thickness variations reaching up to 15 meters. The data interpretation reveals the complex activation history of NNW–SSE normal faults, oblique to the northern margin, during the Late Campanian–Maastrichtian, consistent with observations from the central Adriatic Sea and adjacent onshore areas (Santantonio et al., 2013).

The study demonstrates a different evolution compared to the eastern margin of the Apulia Platform, where N–S normal faults, parallel to the margin, play a key role in controlling the platform-to-basin transition, as indicated by the sedimentological characteristics of the Monte Acuto Formation, which suggest the persistence of a deep-water environment during the Upper Cretaceous (Borgomano, 2000). In contrast, the depositional architecture of the Orfento Formation reveals the transition from a relatively deep-water setting to shallower waters, accompanied by the development of a highly productive rudist-dominated carbonate factory. This indicates the progressive infilling of the northern escarpment, where the faults only locally controlled the production and accommodation zones of the bioclastic sediments along the northern margin.

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The Cenomanian-Turonian rudist carbonate platform of Rocca di Cave (Latium central Apennines): an actualistic vs process-product model

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Keywords: rudist carbonate platform, process-product, gravitational processes.

The rudist rich carbonate platforms have attracted the interest of many carbonate sedimentologists for their peculiarity between the Mesozoic carbonate platforms. Their distinctive aspect is represented by the great ability of the rudists to produce a huge amount of carbonate sediment in order to control the depositional profile of the platform and for their wide diffusion in the Mediterranean and in the Indo-Pacific areas. Notwithstanding their wide diffusion, many contrasting depositional models have been proposed. This is due to the lack of modern analogues even if modern tropical and even temperate examples have been used to interpret these type of platforms. An interesting example is represented by the Rocca di Cave carbonate platform, Cenomanian-Turonian in age. In the south-eastern area of Rocca di Cave rudist and coral rich deposits crop out. In this work a stratigraphic section has been logged and sampled. For the interpretation the classical process-product approach of Luis Pomar has been applied. Lithofacies and microfacies analysis show rudist and coral floatstone-rudstone alternating with bioclastic grainstone. Lithoclasts are common in both lithofacies. Facies characters are indicative of gravitational processes, in particular they are the product of mass transport and carbonate turbidites accumulating along the carbonate platform slope. There is no evidence of preserved bioconstruction in life position. The main components in the investigated sector of the platform derive from dismantling of bioconstructions developing on marginal areas with the contribute of shoal sediments.

The Pliocene deoxygenation event in the Adriatic region: clues from the Fiumana section (Emilia-Romagna, northern Italy)

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Keywords: anoxia, eutropication, thermohaline circulation.

The Mediterranean Sea is undergoing major climate-driven changes, with marine deoxygenation emerging as a critical threat to its ecosystems. Past episodes of oxygen depletion, marked by sapropel deposition and biotic crises, offer valuable analogues for understanding future biogeochemical dynamics and informing mitigation strategies. In this study, we focus on a middle Pliocene deoxygenation event (~3.036 Ma), evidenced by the deposition of a sapropel. This event occurred during a period when global temperatures were within the range projected for the end of this century under a business-as-usual scenario. The event is recorded in the Fiumana section (Emilia-Romagna, northern Italy), which featured hemipelagic sedimentation in the marginal setting of the paleo-Adriatic Sea.

We conducted micropaleontological analyses (calcareous nannofossils and foraminifera), along with sedimentological, stable carbon (δ13C) and oxygen (δ18O) isotope analyses. These investigations aimed to reconstruct the paleoenvironmental conditions in an area crucial for investigating the dynamics of Adriatic deep-water formation, which controls deep ventilation in the eastern Mediterranean Sea.

Sedimentological data reveal predominantly laminated sediments, interrupted by millimeter-thick massive layers, interpreted as pulses of terrigenous sediment supply from continental runoff events. Lamina-scale analysis of calcareous nannofossils supports this interpretation, showing increased reworking within the massive layers. Benthic foraminiferal assemblages also suggest strong runoff influence, with high abundances of inner shelf and oxyphilic taxa displaced from shallower marginal environments. Variability in the calcareous nannofossil assemblages appears to be primarily related to changes in sediment reworking from the continent, driven by continental runoff. However, several μm-scale laminae composed of monospecific nannofossil taxa (e.g., *Braarudosphaera bigelowii* and *Helicosphaera sellii*) indicate episodes of rapid biogenic sedimentation under eutrophic conditions. Species-specific δ18O data (*Orbulina universa, Globigerinoides rube,* and *Globorotalia bononiensis*) indicate surface water freshening and/or warming during sapropel deposition. These changes, coupled with increased nutrient input, likely triggered the onset of oxygen-depleted conditions.

We conclude that local riverine input, likely from the emerging Apennine chain, played a major role in enhancing surface productivity and weakening thermohaline circulation, ultimately leading to deoxygenation in the Adriatic Sea. Given the key role of the Adriatic Sea as deep-water formation site, this change likely had cascading effects on oxygenation across the entire Eastern Mediterranean basin.

A Multiproxy Integrated Stratigraphy of the Piacenzian Succession of the Valdelsa Basin (Tuscany, Italy)

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Keywords: Piacenzian, chronostratigraphy, integrated stratigraphy.

The Valdelsa Basin is one of the wider and most important Neogene basins of Southern Tuscany (Italy) and represents a key geological archive for reconstructing the Pliocene depositional and paleoenvironmental evolution of the hinterland of the Northern Apennine. Within the CARG project, a field survey has been carried out in the Sheet 286 (Poggibonsi) aimed at updating the geological cartography, including new measurements of stratigraphic sections integrated with several multiproxy data methodologies providing age constraints. This study investigates the Pliocene succession outcropping in the central-eastern Valdelsa, which consists of shallow-water marine, transitional and continental sediments, using an integrated stratigraphic approach, combining physical stratigraphy with sedimentary facies analysis, micro- and macropaleontological content, planktic foraminiferal biostratigraphy, paleomagnetic and chemical investigations. The succession deposited during the Piacenzian and in particular during the mid-Pliocene Warm Period (2.9-3.3 Ma according to Lisiecki & Raymo, 2005), from the upper part of the MPL4b to the MPL5a Zones according to the foraminiferal zonal scheme of Lirer et al. (2019). The analysis of the Characteristic Remanent Magnetization (ChRM), integrated with biostratigraphy, allows to individuate two magnetic inversions, from C2An.2r to C2An.2n and C2An.2n to C2An.1r. Other magnetic properties such as magnetic mineralogy and Anisotropy of Magnetic Susceptibility of marine and continental deposits have been also investigated. The physical bio- and lithofacies correlations allow to delineate the stratigraphic architecture with palaeoecological and paleoenvironmental insight whereas the chronostratigraphic framework has been refined with new bio- and magnetostratigraphic proxy data. Furthermore, the comparison of the updated chronological proxy data with the global benthic $\delta^{18}O$ stack, providing a more precise identification of the main climatic events related to the depositional evolution of the central-eastern sector of the Valdelsa Basin during the Upper Piacenzian.

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Reconstructing demises and renewals of a Carboniferous isolated carbonate system by detailed sedimentological core study: insights from the Kashagan platform (Pre-Caspian Basin, Kazakhstan subsurface)

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Keywords: Carboniferous, Kashagan, pre-Caspian Basin.

In the Carboniferous several carbonate systems developed on the margins of the Pre-Caspian basin in the form of large isolated rimmed platforms. Many of them now are hydrocarbons bearing reservoirs having excellent petrophysical properties. One of the largest is the Kashagan system discovered in 2000 in the northern Caspian Sea (off-shore Kazakhstan). The reservoir was intensively cored since the early appraisal phase.

A model of evolution of the Kashagan platform has been reconstructed through facies analysis and paleo-biological community determination conducted on about 1000 meters of core from wells investigating the inner and the margin domains of the platform. Macro- and micro-scale core analysis of components and sedimentary structures demonstrated that frequency and velocity of the sea level fluctuations, in combination with the carbonate productivity and the subsidence rate, ruled repeated demises and renewals of the Kashagan platform along the Carboniferous time.

Since the Late Devonian the Pre-Caspian basin was under favourable paleoclimatic conditions for the flourishing of many carbonate-fixing organisms in shallow water settings. From the early Carboniferous, a slow and progressive increasing of the subsidence rate, triggered by regional tectonic events and concomitant to a sea level rise phase, created space for accommodating hundreds of meters of carbonate sediment. The Kashagan platform architecture, increasingly delineated, consisted of a quite continuous bio-constructed margin surrounding the inner lagoon setting and an outer steep slope. The paleo-biological community (calcareous algae, benthic foraminifers, rugose and tabulate corals, calcareous sponges, and many microbial forms) was rich, well diversified, and strongly responding to the dynamic environmental changes. This led to the deposition of stacked relatively deep and shallow water facies which recorded transgressive and regressive phases and depicted V and IV order shallowing upward cycles.

A subsequent phase of progressive sea level fall, starting in the Upper Visean and continuing through the Serpukhovian, reduced the accommodation space driving the system to develop laterally (prograding phase), resulting in thinner depositional cycles. During this phase, shallow facies became dominant and subaerial exposure events occurred periodically (temporary switch-off of the carbonate productivity). The prograding phase ended in the Serpukhovian with a major subaerial exposure event leading to the development of soil layers and strong meteoric alteration. From this phase onwards, during the Bashkirian time, the platform system continued surviving under very shallow conditions, with amalgamation of thin depositional cycles related to high frequency sea level fluctuations. Several subaerial exposure events occurred, and superimposed karst had a significant impact on reservoir properties.

The Eocene-Oligocene transition (EOT): a study through calcareous nannofossils from IODP Site U1553 and comparison with other ODP Sites

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Keywords: nannofossils, proxy, paleoecology.

Paleoclimatic changes in the Southern Ocean during the Eocene-Oligocene interval were studied by analyzing calcareous nannofossils from 809 samples from Site U1553 (IODP Leg 378, Campbell Plateau, New Zealand) (Raffi et al., 2024). The succession, analyzed at high resolution, consists of a 79 m composite core corresponding to an interval of about 5 Ma. The nannofossil assemblage is generally well preserved. Compared to previous studies, for this project, the sampling resolution near the EOT was reduced to 5 cm to highlight otherwise unobservable point-like climatic fluctuations. A Principal Component Analysis (PCA) was performed on the Site under study to identify any palaeoecological preferences in the calcareous nannofossil assemblage. Following the biostratigraphic determinations, the results obtained were correlated with other sites (ODP 689D, 738B, 748B, 744A and 1090B) (Villa et al., 2014) to evaluate the climatic evolution on a larger spatial scale. This study improves the paleoecological, paleoceanographic and paleoclimatic reconstructions of the transition from greenhouse to ice conditions.

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3D reconstruction and depositional architecture of the Monte Agnello Carbonate Platform (Dolomites, Italy)

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Keywords: Triassic, carbonate platform, 3D reconstruction.

This study presents a comprehensive geological and three-dimensional reconstruction of the Monte Agnello carbonate platform, located in the south of the Latemar Mountain within the Dolomites (Northern Italy). Despite its close proximity to the well-studied Latemar platform, Monte Agnello has received comparatively little attention in the literature. Its geological significance lies in its location adjacent to the Middle Triassic Predazzo intrusive complex and in the well-preserved stratigraphic record that documents the evolution of carbonate depositional systems during a critical phase of tectono-magmatic activity.

The platform is built upon a complete Permian–Triassic sedimentary succession that includes the Werfen Formation, evaporitic and dolomitic intervals of the Serla Dolomite, and the Contrin Formation. On this substrate, an isolated carbonate platform of the Sciliar type developed during the late Anisian to Ladinian stages. Field mapping and facies analysis were conducted to reconstruct the architecture and zonation of the carbonate body. Two principal depositional domains were identified: an aggradational domain to the south, marked by sub-horizontal bedding and facies indicative of inner platform environments, and a progradational domain to the north, dominated by slope deposits, clinoform geometries, and massive, structureless lithologies associated with margin and slope transitions. These interpretations were validated through stratigraphic sections and microfacies analysis from key outcrops such as Baito Valbona and Baito La Bassa.

To complement the field data, a high-resolution three-dimensional geological model of the Monte Agnello platform was constructed using Schlumberger Petrel® software. The model integrates multiple data sources, including a 1x1 m DTM, lithostratigraphic boundaries from field surveys, and georeferenced geological cross-sections. Picking of stratigraphic horizons and modeling of tectonic discontinuities allowed for the creation of a spatially constrained structural and depositional framework. The model effectively differentiates between the aggradational and progradational sectors by mapping the extent and geometry of slope-related facies. Furthermore, six major fault systems were modeled, which fragment the platform and some of them correspond with regional structural alignments associated with the broader evolution of the Dolomites during the Middle Triassic.

This integrated approach provides new insights into the interaction between carbonate platform development, syn-depositional tectonics, and volcanism. The results contribute to a more nuanced understanding of how the emplacement of magmatic bodies, such as the Predazzo intrusion, influenced carbonate sedimentation and deformation in the surrounding area. The model offers a scalable methodology applicable to other carbonate systems and establishes a valuable foundation for further studies on the evolution of Triassic platforms within the Southern Alps.

Depositional and diagenetic imprints of peritidal cyclicity and *hiatuses* in the Mesozoic shallow-water carbonates of the Eastern Mediterranean

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Keywords: shallow-water carbonates, hiatus, Eastern Mediterranean.

The Eastern Mediterranean, with its complex geological setting, is a key region for studying carbonate systems. It hosted long-lived shallow-water carbonate platforms that developed on remnants of hyperextended continental crust rifted from Gondwana during the Triassic–Early Jurassic.

Within this framework, the Eratosthenes High and its appendixes are ideal for understanding the evolution of isolated Tethyan carbonate platforms during the Mesozoic. Subsurface data provide valuable insights into the intricate interplay of tectonic, depositional, and diagenetic processes that have shaped such carbonate systems. Their stratigraphic record is punctuated by subaerial exposure events and regional *hiatuses*, reflecting the influence of both sea-level fluctuations and tectonics. These *hiatuses*, whether related to *non*-deposition or erosion, have significant impact in terms of diagenesis, adding complexity to the interpretation of these carbonate systems for reservoir characterization purposes.

This study is based on the analysis of rock samples (cuttings and cores, about 650 samples) collected from several well sections in the Eastern Mediterranean. Each sample has been examined to characterize its facies, non-skeletal and skeletal components (particularly microfossils for biostratigraphic purposes), diagenetic overprint, including petrographic and geochemical isotopic signatures.

Among the multiple *hiatuses* observed within the platform succession, a regional, diachronous/time-transgressive, “Middle Cretaceous” unconformity/*hiatus* marks the top of the whole shallow-water carbonate sequence. This unconformity is the result of key phases of Mesozoic platform demise and drowning, during which shallow-water carbonates were subsequently replaced by uppermost Mesozoic and Cenozoic pelagic deposits.

A sample-based approach is essential, as subsurface investigations in this area are often limited by overall low-resolution of seismic imaging, primarily due to the presence of a thick Messinian evaporitic sequence.

The recorded Mesozoic shallow-water sequences primarily consist of meter-scale peritidal cycles, characterized by stacked lagoonal to tidal flat facies associations. Though this cyclicity is evident along all the studied well sections, the impact on carbonates (especially in terms of diagenesis) seems to be markedly associated with the recorded major regional sequence boundaries and unconformities. In this regard, it seems evident that early diagenesis, whether marine, meteoric, or shallow burial-related, has exerted a strong control in terms of dissolution and cementation processes. Isotope and geochemical data as well support a predominantly shallow-water diagenetic environment shaping the reservoir properties of the studied sequences.

The role of the Mediterranean area as a Quaternary refugia: a palaeoecological perspective based on herbivorous ungulates dietary adaptations through the Pleistocene

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Keywords: Quaternary, dental wear patterns, Pleistocene.

The last ~2.6 million years were marked by significant climatic upheavals linked to the initiation and consolidation of the Quaternary glacial cycles, that radically changed European terrestrial biomes. These events were followed by major faunal turnovers with the dispersion and radiation of multiple mammal groups, including the genus *Homo*. The significant endemism and genetic diversity observed in the fauna and flora of the Mediterranean Peninsulas suggest that European southernmost areas acted as primary refugia during Pleistocene glacial periods. Here we investigate the role played by the Iberian and Italian Peninsulas as well as the Mediterranean France in the persistence of mammal species during major Quaternary climatic events. We review dietary information based on dental wear data of fossil herbivorous ungulates. They are greatly susceptible to change in vegetation composition in relation with climatic shifts (e.g., the Middle Pleistocene Transition, Heinrich and Dansgaard-Oeschger events). Furthermore, we compare our data with paleoclimatic models obtained from the novel *pastclim* R package developed by Leonardi et al. (2023) to test if habitat reconstructions based on ungulates dietary information are in accordance with environmental predictions based on global circulation models (e.g., HadCM3, also used in the IPCC Assessment Reports). Preliminary results suggest that dental mesowear patterns generally follow annual mean temperatures variations during the Pleistocene, while correlation with other environmental variables such as annual precipitation is less clear.

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High productivity, carbonate chemistry shifts, and cooling at the Eocene-Oligocene boundary: The global signal of *Clausicoccus subdistichus*

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Keywords: calcareous nannofossil, Eocene-Oligocene, paleoclimate.

The Eocene-Oligocene transition (EOT; ~34 Ma) marked the shift in Earth's climate from a warmhouse to a coolhouse state and the development of extensive ice-sheets on Antarctica (Westerhold et al., 2020). This major climatic phase coincided with a sudden increase (acme) of the calcareous nannofossil *Clausicoccus subdistichus*, documented across a wide range of geological records, from on land sections to deep-sea drilling sites. Although this taxon has long been recognized for its biostratigraphic utility, its ecological role and response to Antarctic glaciation have remained largely unexplored.

Here, we present new morphometric and abundance data for the *C. subdistichus* group - including *C. subdistichus* and *C. fenestratus*—from multiple ocean sites: Ocean Drilling Program (ODP) Site 756 in the Indian Ocean, International Ocean Discovery Program (IODP) Site U1509 and ODP Site 1209 in the Pacific Ocean, and IODP Site U1411 in the Atlantic Ocean. Across all study sites, we document a synchronous increase in both size and abundance of this group during the EOT, confirming the global nature of this event.

We interpret the acme of the *C. subdistichus* group as a biological response to two global and interconnected processes. First, the development and expansion of Antarctic ice sheets likely intensified the northward transport of nutrient-rich waters from the Southern Ocean, boosting surface ocean productivity at low to middle latitudes. Second, a concurrent oversaturation of carbonate ions ($[CO_3^{2-}]$) - linked to global shifts in carbonate production and burial (Merico et al., 2008).

These interpretations are further supported by productivity independent proxies, such as opal and benthic foraminifera accumulation rates from the Southern Ocean and low-middle latitudes, respectively, as well as with the notable deepening of the CCD (> 5 km) (Taylor et al., 2023).

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Westerhold T. et al. (2020) - An astronomically dated record of Earth's climate and its predictability over the last 66 million years. Science, 369, 1383-1388.

Unlocking Mediterranean Paleoclimatic Signals from the Last 20,000 Years: The PaleoMED20 Marine Sediment Cores Database

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Keywords: Mediterranean Sea, marine sediment cores, paleoclimate.

Paleoclimatic data from Mediterranean marine sediment cores are essential for understanding past climate dynamics in the absence of modern recording instruments. The strategic location of the Mediterranean Sea between the Atlantic Ocean and surrounding lands provides valuable insights into the interactions between oceanic and terrestrial climate systems. Its relatively small size allows for a rapid and amplified response to past climatic changes (Chiggiato et al., 2023). Reconstructing past climatic variables by analyzing biotic and geochemical indicators (proxies) preserved in marine sediment cores is crucial for forecasting future climate scenarios, especially in light of human-induced impacts such as extreme weather events, carbon emissions, and ocean acidification. Here, we present PaleoMED20, a comprehensive paleoclimatic database that uses nearly six decades of Mediterranean research and spans the last 20,000 years, from the Last Glacial Maximum to the present. The extensive PaleoMED20 dataset integrates data from over 1,500 marine sediment cores, including metadata related to oceanographic cruises and cores, as well as the presence/absence of paleoclimatic data for each core. These paleoclimatic records were compiled through a systematic literature review, incorporating data from publicly available archives such as PANGAEA, NOAA, SeaDataNet, ISMAR, and many web search engines and scientific libraries, including the Scientific Ocean Drilling Bibliographic Database and the UNESCO Digital Library. For each core, we included information on past environmental variables—organized into 11 categories—and their associated quantitative and/or qualitative proxies, categorized by geographic areas within the Mediterranean Sea.

To assess the technical quality and suitability of the database, a subset of 36 well-studied and strategically significant cores was selected to represent various Mediterranean sub-basins and water depths from both the western and eastern Mediterranean, including the Adriatic Sea. This analysis demonstrates how PaleoMED20 serves as a valuable tool for identifying key variables and proxies over the last 20,000 years, while also highlighting existing knowledge gaps.

Moreover, PaleoMED20 facilitates basin-scale comparative climate analyses, offering deeper insights into the spatial and temporal coverage of the main climatic variables across the Mediterranean Sea. Additionally, it can support the strategic planning of future oceanographic expeditions in under-explored areas and serves as a crucial resource for informing decision-making processes, guiding future research to bridge existing knowledge gaps.

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Disappearance and recolonization of ostracod assemblages in an epibathyal environment during sapropel 19 deposition (i-cycle 90, Calabrian Stage, early Pleistocene) in the IM-5 Agosto section (Montalbano Jonico, southern Italy)

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Keywords: ostracods, paleo-oxygenation, sapropel19.

The IM-5 Agosto section, part of the Montalbano Jonico composite section in southern Italy, offers insights into the sensitivity of ostracod assemblages to variations in bottom-water oxygen levels. The section includes a dark, locally laminated interval, 5.6 meters thick, correlated to MIS 25 and associated with sapropel 19 and i-cycle 90 (Maiorano et al., 2004), orbitally tuned at 954 years ago. The deposition of sapropel 19 reflects a period of enhanced freshwater runoff induced by a wetter climate (Maiorano et al., 2008). Increased fluvial erosion, resulting in enhanced terrigenous input and greater surface water turbidity, likely promoted stratification of the water column, which in turn limited deep-water ventilation and contributed to the development of oxygen-depleted conditions at the seafloor. High-resolution benthic foraminiferal investigations (Stefanelli et al., 2005) identified two oxygen depletion phases (phase A and phase C) within the sapropel, separated by a temporary re-oxygenation event (phase B). BFOI calculation, performed on each sample of the section following the method proposed by Kaiho (1994), indicate that during phase A all samples fall within the low oxic range (1.5-3.0 ml/l O_2). In phase C, conditions alternate between low oxic and dysoxic (0.1-0.3 ml/l O2), while post-sapropel samples predominantly fall within the low oxic range. The section, deposited in an epibathyal setting (250-350 m), shows no major bathymetric variations, suggesting oxygen fluctuations as the main control on faunal changes. In this context, a proper estimation of paleo-oxygenation requires distinguishing between autochthonous and allochthonous ostracods, likely transported from shallower settings less affected by water stratification. The occurrence of ostracods even under low oxic conditions supports the hypothesis that they can tolerate oxygen levels below the commonly reported threshold of 3.0 m/l O_2. Some taxa such as *Cytheropteron pseudoalatum, Cytheropteron ruggierii, Henryhowella sarsii sarsii* and *Krithe praetexta*, persist during phase A, although diversity drops compared to pre-sapropel conditions, suggesting oxygen levels near the lower end of the low-oxic range (1.5 ml/l O2). Phase C shows more severe oxygen depletion, confirmed by BFOI and ostracod absence. After the sapropel event, ostracod diversity increases, although oxygen levels remain within the low oxic range, likely approaching its upper limit (3.0 ml/l O_2). Phase B, recognized as a period of re-oxygenation, falls within the suboxic range (0.3-1.5 ml/l O_2) based on BFOI results. However, the presence of ostracods in this interval suggest that oxygen levels were likely higher, highlighting that the Kaiho method, while providing useful insights, may underestimate oxygen levels in some cases. This underscores the importance of a multidisciplinary approach for a more reliable reconstruction of bottom-water oxygen variations, linked to changes in climatic conditions.

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Maiorano P. (2004) - Calcareous nannofossils events in the lower-middle Pleistocene transition at the Montalbano Jonico section and ODP Site 964: calibration with isotope and sapropel stratigraphy. Riv. Ital. Paleontol. Stratigr., 110(2), 547-557.

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The record of the Monterey Event in the Northern Mediterranean: New insights from the carbonate ramp deposits of the Pietra da Cantoni Formation (Tertiary Piedmont Basin, NW Italy)

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Keywords: Middle Miocene, carbonate ramp deposits, chemostratigraphy.

The Monterey Event has garnered renewed interest in recent years due to the significant relevance of the Miocene as a key epoch for addressing past climate and oceanographic perturbations. The Monterey Event represents a major anomaly in the global carbon cycle, characterized by a positive carbon isotope excursion (ranging from +0.02 ‰ to +2.65 ‰; Brandano et al., 2017) that occurred during the "Middle Miocene Climate Optimum" (MCO), between 16.9 and 14.7 Ma. During this interval, atmospheric pCO_2 concentrations were close to or moderately higher than present-day values, while global mean temperatures were higher by approximately 3 to 6°C relative to today. The Monterey Event has been widely recognized in both shallow and deep marine settings; in the Mediterranean region, it has been identified within the carbonate ramp deposits of the Central Apennines and Malta (Brandano et al., 2017; Zammit et al., 2022).

This study focuses on Aquitanian to Serravallian carbonate deposits (Pietra da Cantoni Formation, PdC Fm.) exposed in the Tertiary Piedmont Basin (NW Italy). The PdC Fm. comprises a succession of shallow to deep marine carbonate sediments, ranging from inner ramp rodalgal calcarenites and calcirudites to outer ramp planktic foraminifer-rich calcareous marls.

Sedimentological, petrographic, magnetostratigraphic and biostratigraphic analyses were performed on six stratigraphic sections, accompanied by a detailed chemostratigraphic investigation on one section through bulk-rock analyses of the carbon and oxygen stable isotope composition of 68 samples. The primary objective is to detect the expression of the Monterey Event and evaluate its impact on biogenic sedimentation in the Northern Mediterranean region.

Preliminary results from the chemostratigraphic analysis show that at least five distinct positive δ13C peaks are recorded in the investigated section, allowing correlation with the Monterey event. A negative shift of the $\delta^{18}O$ values, possibly recording the MCO, has been also observed but further analyses are needed. These data will contribute to the reconstruction of the paleoenvironmental evolution of the Northern Mediterranean sector during the Middle Miocene and will allow correlation of the studied succession with analogous deposits exposed in other Mediterranean sites.

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Gilbert-type delta foreset deposits as records of changes in sediment supply dynamics

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Keywords: Gilbert-type deltas, foresets, grain-size.

Gilbert-type deltas present distinctive tripartite sedimentary bodies consisting of a fluvial delta plain topset, a steeply inclined foreset of subaqueous delta-slope deposits, and a sub-horizontal bottomset consisting of prodelta deposits (e.g., Gobo et al., 2015).

A determining component of a Gilbert-type delta is its narrow delta brink, which facilitates the transfer of sediment from the delta plain topset to the delta front. It regulates the overall sediment distribution trend along the slope, based on the available accommodation space and the degree of sediment storage or bypass. The resulting sedimentary architecture is an alternation of sigmoidal and oblique toplap geometries that are preserved at the topset-foreset transition. These geometries are indicative of a base level rise in the former case and of a base level fall or stillstand in the latter case. Additionally, being accumulated below the base level, foreset deposits of Gilbert-type deltas can serve as a continuous archive of changes in sediment supply or accommodation space affecting the delta during its entire lifespan.

These architectural features make Gilbert-type deltas valuable archives for documenting recurrent variations in accommodation space (e.g., relative sea-level changes) or sediment supply (e.g., river discharge pulses) both on Earth (Gobo et al., 2015) and on Mars (Mangold et al., 2021). For these reasons, outstanding exposures of Pleistocene Gilbert deltas of the Corinth Rift (Greece) have been selected to unravel the link between sediment distribution across the delta brink zone and relative forcings.

Sedimentological and architectural data on sigmoidal foreset geometries, where the genetic relationship between topset and foreset beds is evident, were collected in the field during ground-based field surveys, as well as through the analysis of images and 3D photogrammetric models obtained from drone surveys. Grain size variations in topset and foreset beds were analyzed to establish a relationship between the sediment transport capability of the feeder topset and the sediment trapping efficiency of the associated delta front. Establishing such a relationship would allow the reconstruction of variations in sediment supply to the delta, even where topset beds are not preserved. The results of this study can provide insights into changes in sediment supply dynamics in deltaic systems associated with specific climate variations both on Earth and on Mars.

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S16.

TIMES - Unlocking Earth's climate in the geological record: advances in paleoclimate reconstruction and proxy data applications

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Quaternary subsurface integrated stratigraphy of the Brescia area: New evidences from the CARG BS1 scientific drilling (N-Italy)

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Keywords: Central Po Plain, sedimentary evolution, chronostratigraphy.

We present a multidisciplinary investigation of a 150-m-thick sedimentary succession recovered from a borehole (CARG BS1) drilled South of the Brescia metropolitan area (N-Italy) within the framework of the CARG Project (1:50,000 Geological Map of Italy, Sheet 121 Brescia). The CARG BS1 core provides a high-resolution stratigraphic record aimed at refining the subsurface geological framework of the central Po Plain, specifically in the sector bounded to the North by the Mesozoic Alpine outcrops and to the southeast by the tectonic reliefs of Castenedolo and Ciliverghe. The PS1 PS2 and PS3 depositional sequences and the magnetostratigrafically-calibrated R and Y regional unconformities represent the paleoenviromental evolution from a shallow marine to a continental setting in the last 2 Ma (Carcano & Piccin, 2002; Aghib et al., 2024). In the CARG BS1 record, the R-surface is identified at 103.42 mbrf, based on magnetostratigraphic and biostratigraphic constraints between the top of the Jaramillo polarity subchron (ca. 990 ka) and the Brunhes-Matuyama boundary (780 ka). An interpolated age of ~870 ka is attributed to this surface, corresponding to MIS 22 (Muttoni et al., 2003). The R-surface marks the transition between the PS1 and PS2 stratigraphic units.

The Y-surface, at a depth of 43.41 mbrf, at the base of the PS3 sequence, is less well constrained chronologically, with an indicative age of approximately 0.45 Ma (Carcano & Piccin, 2002). The PS1 sequence is composed mainly of fine-grained sediments, representing a shallow marine depositional environment associated with phases of fan-delta progradation. It is attributed to the Calabrian (*pro parte*) based on foraminiferal biostratigraphy (macro- and microfossil assemblages) and the presence of a partial record of the Jaramillo subchron. The uppermost part of PS1contains a fine-grained laminated interval suggesting brackish conditions passing upward to continental facies as revealed by the macro- and microfossil content, ostracods, foraminifera (*Aubignyina perlucida* and *Ammonia tepida*), and by the pollen types (*Tsuga, Carya*) typical of an Early Pleistocene age. The PS2 sequence (103-43 mbrf) consists of gravel/sandy gravels to silt/sands with sparse fresh-water ostracod assemblages, representing meandering/distal braided fluvial to glacifluvial systems influenced by climatic cooling, as confirmed by the disappearance of plants recorded in the lowermost core section. Moreover, the sand/clast petrography allowed to identify the Garda and Val Trompia basins as source areas. The PS3 sequence above the Y-surface at 43 mbrf represents proximal braided glacifluvial/proglacial setting, mostly consisting of massive unsorted sedimentary gravels related to the Pleistocene glacial advances.

The extensive multidisciplinary characterization of the CARG BS1 record allowed to establish a reference bio-chronostratigraphy for the study of the Quaternary sedimentary evolution of the central Po Plain.

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Combined intra-tooth isotope and proteomic analyses reveal the paleoecology of straight-tusked elephants at Neumark-Nord (~125 ka, Germany)

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Keywords: strontium isotopes, mobility, LA-MC-ICPMS.

The Last Interglacial site complex of Neumark-Nord (~125 ka) preserves the largest known assemblage of straight-tusked elephants (*Palaeoloxodon antiquus*) within a lake-dotted landscape surrounded by a semi-open environment. Along the lakeshores, remains of over 70 individuals bearing anthropogenic cut marks—primarily adult males—suggest targeted Neanderthal hunting. To investigate mobility patterns, highly spatially-resolved laser ablation MC-ICPMS analyses of $^{87}Sr/^{86}Sr$ ratios were conducted *in situ* on four molar cross-sections. A custom-developed strontium isoscape allowed reconstruction of provenance and movements. These data were integrated with sequential $\delta^{18}O$ and $\delta^{13}C$ intra-tooth profiles obtained via IRMS to assess seasonal shifts in habitat use and diet. Enamel amelogenin analysis via LC-MS/MS found three males and one female individuals. Notably, substantial intra-tooth $^{87}Sr/^{86}Sr$ variation across all individuals indicates (sub-) seasonal mobility over approximately eight years of tooth formation. Two elephants spent extended periods in radiogenic regions, likely near Paleozoic uplands up to 300 km from Neumark-Nord. Isotopic signatures ($\delta^{18}O$ and $\delta^{13}C$) of these non-local individuals suggest they foraged in more forested habitats and consumed more ^{18}O-depleted water compared to local counterparts. This integrated multi-proxy approach offers unprecedented insight into the behavioral ecology of *P. antiquus* and underscores the role of selective Neanderthal hunting strategies within dynamic Late Pleistocene landscapes.

AI-Driven Interpretation of paleoenvironmental proxies: prospects and limitations

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Keywords: AI, Permian, ichnology.

This study investigates the application of artificial intelligence (AI) in the analysis of proxy data, focusing on sedimentological and paleontological records associated with the Bolzano Supervolcano. The Bolzano Supervolcano, recognized as the largest Permian supervolcano in Europe, provides a rich record of geopaleontological data for evaluating the efficiency of AI in proxy data interpretation. Volcanic activity spanned approximately 11 million years (285-274 Ma) and resulted in freshwater sedimentary deposits that preserve an extensive paleontological record, including vertebrate and invertebrate trace fossils, plant remains, conchostracans, and rare vertebrate fossils.

Our research show that AI is a promising tool in enhancing field detection of geological proxies. We developed IchnoFinder, an AI system based on a convolutional neural network architecture, which has been trained on a dataset comprising 100,000 labeled images. The results from this study indicate that IchnoFinder achieves an accuracy rate exceeding 80% in detecting bioturbated outcrops. Noteworthy findings include the identification of simple, unbranched *Planolites* at locations such as Silberhof, Sesto, and Gocciadoro, as well as millipede trails, specifically *Diplopodichnus*, at Monte Luco. Despite these promising results, the explainability analysis of the AI system revealed certain limitations. The system exhibited a tendency to rely on the presence of large white clasts as an indicator of unbioturbated outcrops. This finding emphasizes the necessity for further refinement of the AI model to ensure more robust and accurate identification processes. Enhancements in the system framework could potentially lead to its integration with wearable technology, such as smart glasses, facilitating real-time ichnofossil detection in field settings.

The integration of AI into proxy data analysis has yielded promising results for paleoenvironmental reconstructions. In our study, we developed an AI application designed to interpret stratigraphic logs. The tool is powered by GeologyOracle, an AI-based geoscience assistant that synergizes the capabilities of GPT-4 with an extensive Earth Science literature database. This tool interprets paleoenvironmental data by analyzing sedimentological attributes, ichnological indicators, and body fossil taxa. The stratigraphic log analyzer processes these inputs to generate a comprehensive textual paleoenvironmental interpretation. For instance, our tool revealed a terrestrial palaeoecosystem characterized by the presence of hyperconcentrated debris flows. GeologyOracle has proven highly effective in refining scientific manuscripts and generating visual reconstructions of Bolzano paleoecosystems, showcasing AI potential to enhance geoscience research. In conclusion, while AI significantly can significantly advance interpretation of proxy data, the integration of human expertise is vital to ensure the precision of AI-driven outputs.

Buried soil dark horizons as climate proxies: a geochemical study from Bologna area

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Keywords: soil, C isotopes, climate.

Dark soils known as Black Horizons (BHs) have been identified and studied in various areas within the territory of Bologna (Bianchini et al., 2022). BHs are buried soils found in different regions of the world (e.g.: Spain, Germany, Greenland). In addition to their color, they are also characterized by a low concentration of carbonates and the presence of microcharcoal. BHs form as a result of environmental and climatic alteration cycles that occur repeatedly during cooling periods in a given area (i.e., glaciation).

This work aims to reconstruct the genesis, composition, and environmental significance of dark soils identified in the core sample collected at the site known as SOR3, located in the external courtyard of the S. Orsola Hospital in Bologna.

The soil samples were analyzed through detailed geochemical analyses, particularly elemental and isotopic carbon analyses using an elemental analyzer coupled with an isotope ratio mass spectrometer, to distinguish organic and inorganic components. The obtained data were then correlated with previous data on soil texture and composition from Bizzarri's (2021) thesis.

Bianchini G. et al. (2022) - Late Glacial and Holocene buried black soils in Emilia (northern Italy): genetic and paleoenvironmental insights. J. Soils Sediments, 22, 409-428, https://doi.org/10.1007/s11368-021-03088-6.

Bizzarri S. (2021) - Nuovi dati stratigrafici e geopedologici dall'area dell'ospedale S.Orsola (Bologna). Tesi di Laurea in Scienze Geologiche, Università di Bologna.

Tracing LIP-related volcanic winters from a within-magma perspective

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Keywords: Large Igneous Provinces, sulfur, clinopyroxene.

Large Igneous Province volcanism was a major and versatile driver of climate and environmental change, and the largest contributor to dramatic global changes and extinctions in the geologic record. Volcanism perturbs climate through the release of greenhouse gases (mostly water, carbon dioxide, and methane), and the discharge of sulfur dioxide, which is a cooling agent if injected high enough to reach the stratosphere. These forcings result, respectively, in long-term global warming and short-lived volcanic winters. Humans witnessed volcanic winters during historical eruptions (e.g. the basaltic 1783-84 Laki fires or the explosive 1991 Pinatubo eruption), capable in some cases of societal impacts. During Large Igneous Province (LIP) emplacement, a growing body of literature recognizes volcanic winters as key short-term climate perturbations, often superimposed on long-term warming trends (e.g. Black et al., 2018; Callegaro et al., 2023; Vickers et al., 2020). These transient cold spells, caused by sudden stratospheric injection of sulfur-rich gases, can be critical stressors for ecosystems and potential drivers of mass extinctions, but they are too brief to leave resolvable signatures in the stratigraphic record, posing a major challenge for their detection in deep time. S-isotope perturbations and glendonite deposition are being explored as sedimentary proxy records of cold snaps during hyperthermals. We propose the alternative approach of tracing volcanic winters from a within-magma perspective, by detecting S-rich magmatic pulses that had the potential of causing volcanic winters (Callegaro et al., 2020; Callegaro et al., 2023). This is done by measuring sulfur concentrations in clinopyroxene in situ by synchrotron-light micro-X-ray fluorescence. Clinopyroxene crystallizes early and near ubiquitously from LIP basaltic magmas, and its S concentrations allow calculation of S concentrations in the equilibrium melt by applying a previously established partition coefficient. We successfully applied this approach (Callegaro et al., 2023) to the Deccan Traps lava piles (Western Ghats, India), where lavas emplaced just prior to the extinction interval show the highest sulfur concentrations, whereas later basalts are generally sulfur poor.

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Chamelea gallina growth declined in the Northern Adriatic Sea during the Holocene climate optimum

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Keywords: climate change, Adriatic Sea, mollusks.

The fossil record of past climate transitions offers insights into future biotic responses to climate change. Here, we compare shell growth dynamics, specifically linear extension and net calcification rates, of the bivalve *Chamelea gallina* between Northern Adriatic Sea assemblages from the Holocene Climate Optimum (HCO, 9-5 kyr cal. B.P.) and today. This species is a valuable economic resource, currently threatened by climate change and numerous anthropogenic stressors. During the HCO, regional sea surface temperatures were warmer than today, making it a potential analog for exploring ecological responses to increasing seawater temperatures predicted in the coming decades. By combining standard aging methods with reconstructed sea surface temperatures (Cheli et al., 2021), we observed a significant reduction in linear extension and net calcification rates in warmer HCO assemblages. During the HCO, immature *C. gallina* specimens developed a denser shell at the expense of a linear extension rate, which was significantly lower than modern specimens. This resulted in an average delay of 3 months in reaching sexual maturity, which is currently reached after 13-14 months or at a length of ~18 mm. This study sheds light on the natural range of variability of *C. gallina* over longer time scales and its potential responses to near-future global warming.

Cheli A. et al. (2021) - Climate variation during the Holocene influenced the skeletal properties of *Chamelea gallina* shells in the North Adriatic Sea (Italy). PLoS One, 16, e0247590, doi.org/10.1371/journal.pone.0247590.

Climatic variability during MIS3 in Eurasia linking to Hominin populations dynamics

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Keywords: speleothems, Eurasia, paleoclimate.

The extinction of *Homo neanderthalensis* occurred in Eurasia around 42 ka. Among the possible causes, the role of climate requires further studies. The aim of this work is to characterize the climatic variability of this region during the MIS3 and the last glacial period through comparison of depositions properties and $\delta^{18}O$-$\delta^{13}C$ records of two stalagmites - AG1 and ZAK9- collected in Agios Georgios (Greece) and Zakariaskldee Cave (Georgia) respectively. These stalagmites were deposited between 57.7 ± 0.24 and 12.1 ± 0.36 ka (AG1) and from 84 ± 0.31 to 34.6 ± 0.53 ka (ZAK9). Both records show a similar trend with an average temporal resolution of about 30 years for AG1 and 20 years for ZAK9. A notable hiatus occurs in ZAK9 between 45 and 35 ka, matching with Heinrich Event 4 (HE 4). In AG1, $\delta^{18}O$-$\delta^{13}C$ records show an interval of less negative values constrained between two negative peaks at 48 ka and 35 ka. This may indicate a possible period of precipitation's decrease, consistent with the lack of deposition in Georgia and the development of HE4. Additionally, this interpretation is supported by a decrease in speleothem growth rate during this interval. These novel high-resolution records are discussed in the context of Eurasian paleoclimate and Neanderthals population dynamics.

Comparative Geobiological Analysis of Coralligenous from Marzamemi and Isola Capo Rizzuto (Southern Italy): insights for environmental perturbations

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Keywords: bioconstruction, microfacies characterization, environmental proxies.

Coralligenous bioconstruction represents one of the most complex and heterogeneous marine habitats in the Mediterranean Sea, characterized by high biodiversity, structural complexity and sensitivity to environmental changes.

This study presents a comparative analysis of two coralligenous build-ups: Marzamemi bioconstructions (Sicily) and build-up within the Isola Capo Rizzuto Marine Protected Area (Calabria). The research focuses on the microfacies composition and internal framework of these systems, aiming to explore their geobiological development and assess their potential as environmental archives.

At both areas, the bioconstruction framework is formed by skeletal and non-skeletal carbonate components. Crustose coralline algae are the dominate skeletal components, followed by bryozoans, serpulids, sponges and molluscs. In both bioconstructions, the skeletal structure is highly porous and include cavity empty or filled by non-skeletal component represented byautochthonous micrite, loose sediment or cement. Sponges play a fundamental role in the morphological development of coralligenous build-ups, not only by influencing their external and internal architecture through growth direction control and bioerosive activity, but also by promoting the *in situ* deposition of autochthonous micrite *via* organomineralization processes induced by their soft tissue .

The Isola Capo Rizzuto build-up shows strong similarities whit those from Marzamemi, supporting the hypothesis of shared processes across different Mediterranean contexts. However, variations in skeletal assemblage proportions, cavity, micrite type and distribution, may reflect environmental differences, possibly related to hydrodynamic conditions, climatic and/or anthropogenic influences.

In addition to microfacies characterization, this study aims to explore the potential relationship between carbonate components and the surrounding seawater chemistry, as observed in the coralligenous build-ups from the Marzamemi area (Bracchi et al., 2022, Cipriani et al., 2024). Geochemical analyses may indicate enrichment in trace metals, which could suggest the presence of environmental perturbations. These geochemical anomalies, recognised in both skeletal and non-skeletal components, might highlight the potential of coralligenous carbonates as *proxies* for environmental monitoring and record of the chemical marine evolution. This integrated approach could reveal that carbonate components of coralligenous provide valuable indications of environmental change. If confirmed, the combination of microfacies analysis and geochemical data may offer a useful framework for assessing past and recent dynamics in Mediterranean marine ecosystems, potentially contributing to future conservation strategies of vulnerable habitats.

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Cipriani M. et al. (2024) - Origin and role of non–skeletal carbonate in coralligenous build–ups: new geobiological perspectives in biomineralization processes. Biogeosciences, 21, 49-72, https://doi.org/10.5194/bg-21-49-2024.

The geochemical signature of progressive isolation of a basin: The Upper Miocene, Central Mediterranean record (Central Italy)

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Keywords: Late Miocene, Mediterranean, stable isotopes.

The "Messinian Salinity Crisis", associated with extensive gypsum and halite precipitation in the Mediterranean, is one of the most studied phenomena by sedimentologists and stratigraphers worldwide, since the first discovery of the evaporites in the 1970s. Recently, several studies reported paleontological and geochemical evidence of progressive isolation, stratification of the water column and detrimental conditions for the benthic fauna, before the onset of the gypsum precipitation. To identify the environmental changes and the consequences of restricted circulation during Late Miocene, we analysed the $\delta^{18}O$, $\delta^{13}C$ and redox-sensitive trace element concentrations in two Tortonian-Messinian marly formations belonging to the different domains of the Central Apennines: The *Orbulina* Marls formation in the Latium-Abruzzi, and the *Turborotalita multiloba* Marls formation in the Apulian Domain (Central Italy). Stratigraphic constraints are provided by calcareous nannofossil biostratigraphy.

During the Late Miocene, the Latium-Abruzzi Domain experienced a progressive deepening of the sedimentary environment marked by the drowning of the Miocene carbonate platform and the onset of the hemipelagic sedimentation of the *Orbulina* Marls in the Tortonian. Then, in the Messinian, the Flysch deposition marks the transition from a foreland to a foredeep system. Conversely, during the same stratigraphic interval, the Apulian Domain developed in an undisturbed foreland characterized by a shallowing of the depositional environment and an increase of the terrigenous content with respect to carbonate production. Preliminary results indicate the onset of enhanced stratification of the water column. In fact, at the base of the Messinian planktonic foraminifera thrive in surface waters in the Latium-Abruzzi domain, while organic matter and redox-sensitive conditions start occurring at the bottom of the water column. Carbon and oxygen isotope ratios -analysed on separated *Orbulina* specimens- reflect the complex evolution of the seawater chemistry, affected by multiple controlling factors. The carbon isotope curve correlates with the regional and global Late Miocene carbon isotope signature. Conversely, the Latium-Abruzzi oxygen isotope curve deviates from other Mediterranean and Atlantic records. In this study, we interpret the decrease of the $\delta^{18}O$ as a hint of a salinity decrease of surface waters. This shift, in fact, determined by the increased riverine input at the base of the Messinian, is coherent with the onset of the Flysch deposition.

Relative Sea-Level Changes since the Last Glacial Maximum: Integration of Seismic Stratigraphy, Benthic Foraminifera, and Calcareous Nannofossils in the Sant'Eufemia Gulf (Offshore Calabria, Italy)

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Keywords: sea-level changes, paleoenvironmental reconstruction, Tyrrhenian sea.

A relative sea level (RSL) curve represents the variation in sea level at a specific location and sedimentary basin scale over time. RSL changes are influenced by global eustatic sea-level fluctuation and local factors such as tectonic uplift or subsidence, sediment loading, and glacial isostatic adjustment (GIA). Although relative sea-level curves were proposed for 30 sites along the Italian coast since the Last Glacial Maximum (LGM), these early models faced limitations due to insufficient age markers. This research aims to present a comprehensive curve of relative sea-level variations for the southern Tyrrhenian region, constrained by coastal features, paleoenvironmental data, and age markers across various time intervals from the LGM to the Holocene. We address this study specifically on the Sant'Eufemia Gulf in the southeastern Tyrrhenian Sea. The site was chosen due to its relatively stable tectonic setting, which allows us to isolate and analyze the effects of eustatic sea-level changes on coastal evolution. The study employed an integrated approach, combining multiple methodologies. High-resolution, multichannel seismic profiles were used to reconstruct the architecture and depth of coastal features (e.g. infralittoral prograding wedges and wave-cut platforms). Sedimentological analyses and high-resolution micropaleontological studies of benthic foraminifera and calcareous nannofossils assemblages, complemented by calibrated radiocarbon ages, were used to calibrate the seismic profiles, constrain sedimentation rates, and reconstruct the paleoenvironmental evolution of the study area since the LGM. The proposed RSL curve is robustly constrained by multiple geological markers across a timescale spanning thousands of years. The curve displays a non-linear trend in sea level rise, characterized by several step-like geometries that indicate phases of sea level rise interrupted by periods of stillstand or lowering. The curve presented in this work was compared with RSL curves proposed by previous studies. The latter – first adjusted using the GIA models – include the ICE-X curves proposed by the Peltier research group (e.g. Roy & Peltier, 2017), the ANU curves by Lambeck et al. (2014) and Lambeck & Purcell (2005), and the PaleoMIST curve by Gowan et al. (2021). The comparison indicates that the curve presented here exhibits greater sea level depths during the 17-21 ka interval. From about 17 ka onward, the curve aligns well with the other curves in terms of depth values within the error bar, with the exception of the PaleoMIST curve. However, the proposed curve reveals higher frequency sea level variations, highlighting a more detailed depiction of the RSL path modelled in this work. Accurate reconstructions of past relative sea-level variations are crucial for developing tectonic and paleoenvironmental models, improving predictive modeling capabilities, and elucidating the implications of climate change.

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Roy K. & Peltier W.R. (2017) - Space-geodetic and water level gauge constraints on continental uplift and tilting over North America: regional convergence of the ICE-6G_C (VM5a/VM6) models. Geophysical Journal International, 210(2), 1115-1142, https://doi.org/10.1093/gji/ggx156.

Early Eocene *Alveolina* from Denmark: sign of extreme hothouse climate?

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Keywords: *Alveolina*, EECO, Denmark.

A sample of limestone collected in the North Sea in a region known as Jyske Rev, west of the mainland Denmark contains a rich larger foraminiferal assemblage, dominated by specimens belonging to the genus *Alveolina*. Some thin sections obtained by this sample allowed the recognition of *Alveolina axiampla*, *A. cremae*, and *A. rugosa*, together with *Rotalia*aff. *trochidiformis*.

This assemblage could be therefore referred to the Shallow Benthic Zones (SBZ) 10-11 of Serra-Kiel et al. (1998), which roughly corresponds to the Early Eocene Climatic Optimum (EECO), the warmest period on Earth during the entire Cenozoic.

Until now, the only larger foraminifera signalled from this North Sea region was *Nummulites planulatus,* described by Cotton (2023). *Nummulites* this far north are exceptionally rare with only two other occurrences know from high latitudes on the west coast of the UK (Van Hinte & Wong, 1975; Stoker et al., 1988). The finding of *Alveolina* is even more unexpected, since until now the northernmost occurrences of this genus are from the Paris Basin and Isle of Wight in the UK, some 600 km to the south. The presence of larger foraminifera at relatively high latitudes during the EECO could only be one more evidence of the reduced latitudinal gradient of temperatures which allowed for range expansions of more tropical taxa.

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Where Isotopes Meet: ISOTOPE Virtual Research Environment and the Future of Geochemical Research

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Keywords: isotope VRE, isotope studio, ITINERIS.

Geosciences have long captured human curiosity, fostering interdisciplinary dialogue scientific debate, with the aim to uniting diverse scientific fields such as Geology, Biology, Archaeology, Agronomy, Ecology, Medicine, food authenticity and traceability. Isotopes play a crucial role in all the above-mentioned fields, and in particular have revolutionized our understanding of Earth's history and processes providing crucial insights into the earth system, determining ages of rocks and materials, tracing element origins, and reconstructing past environmental conditions. In an era of significant technological innovation, where high-performance instruments provide great accuracy and precision, an ever-increasing volume of data is being produced across various Research Infrastructures (RIs). However, a true point of convergence for the integration and effective sharing information still seems to be lacking. A Virtual Research Environment (VRE) can serve as this meeting point, promoting coordinated data access, collaboration among diverse scientific communities, and the development of new perspectives in understanding the processes that govern the Earth system. Virtual Research Environment, in fact, supports the principles of Open Science and data FAIRness (data which meet the principles of Findability, Accessibility, Interoperability, and Reusability) and aims to enhance collaboration among researchers and to find appropriate.

Concurrently, innovations in isotope geochemistry-encompassing conventional (H, O, C, N, S), non-conventional (B, Li, Fe, Cu, Zn, Mg), and radiogenic isotopes (Sr, Nd, Pb) - have revolutionized our ability to trace environmental and geological processes. The development of the ISOTOPE Virtual Research Environment (VRE), as part of the ITINERIS Project (PNRR), represents a major leap forward in integrating diverse isotopic datasets and modelling tools into a cohesive, national platform. In this framework, the web application, named "Isotope Studio" (IS) has been developed. The main objectives of Isotope Studio are (i) to collect geochemical data, including stable, non-conventional, and radiogenic isotopes; (ii) to provide stakeholders with the most commonly used tools for data analyses and interpretation; (iii) to enable data sharing among all the involved institutions, with the aim to facilitate data analysis, visualization (e.g., mixing models, ternary diagrams), and collaborative research, unlocking new avenues for understanding Earth's dynamics.

Ferruginous ghosts in the Silurian of the Carnic Alps, Italy

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Keywords: taphonomy, biomineralization, skeletal replicas.

Three-dimensional fossil bodies preserved as ferruginous external coatings or positive casts of originally calcareous organisms were recovered after acid digestion from conodont residues in the Silurian of the Rio Tamer area in the Carnic Alps. Benthic communities (bivalves, trilobites, ostracods, crinoids, gastropods and brachiopods) constitute the major part of the preserved faunal assemblage. This unique preservation has been guaranteed by iron oxides and hydroxides, which replicated the original organisms. The material was characterized by using optical and scanning electron microscopy (SEM), environmental scanning electron microscopy coupled with microanalyses (ESEM-EDX), X-Ray powder diffraction (XRPD) and confocal laser Raman microscopy. The combined results indicated that the skeletal replicas are primarily composed of hematite and goethite, with subordinate amount of birnessite, chamosite, quartz, siderite and amorphous material. Mineralogical data are in good agreement with previous occurrences. Additionally, the presence of carbonaceous material within the coatings suggests a bio-mediated process in crust formation and highlights the role of microbial activity in triggering unique fossil preservation pathways. Similar occurrences were already reported in the Ordovician and Silurian from nearby areas (Ferretti et al., 2012, 2023) to highlight events driving to iron remobilization in the lower Paleozoic of northern Gondwana, often associated to short-term extinction events.

Ferretti A. et al. (2012) - From black-and-white to colour in the Silurian. Palaeogeogr., Palaeoclimatol., Palaeoecol., 367-368, 178-192, https://doi.org/10.1016/j.palaeo.2012.10.025.

Ferretti A. et al. (2023) - Ferruginous biolaminations within the pre-Hirnantian (Late Ordovician) of the Carnic Alps, Austria. Geobios, 81, 167-177, https://doi.org/10.1016/j.geobios.2023.01.007.

Authigenic bioapatite as a proxy of bio-geological events

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Keywords: bioapatite, diagenesis, cell parameters.

Fossil shells are some of the most commonly used archives in studies of past oceanic geochemistry and climate and low-Mg carbonate remains are usually preferred as they are considered relatively resistant to diagenetic alteration. In contrast, the potentiality of bioapatite shells and, especially, teeth and bones, is still largely underestimated. Vertebrates experimented calcium phosphate to grow their skeletal support and to shape their teeth, while some invertebrates sheltered their soft parts within apatite shells. The plasticity of bioapatite enabled different but extremely successful life strategies in the sea, on the land and in the sky.

Bioapatite, with the general formula $Ca_5(PO_4,CO_3)_3(F,OH)$, is a crystal phase enclosing a variety of chemical compositions. (Bio)apatite crystallizes in the hexagonal system and its crystallographic cell parameters and dimension mirror the iso- and hetero-valent chemical substitutions that may occur in the various coordination sites that, additionally, impart distinctive features and functionality to the phosphatic materials. Chemistry and crystal structure may vary *in vivo*, due to metabolic processes to adapt to the specific functions that bioapatite is requested to perform, or *post mortem* during fossilization and diagenetic processes (Medici et al., 2020).

Several analytical techniques were applied to trace the chemical substitutions, mostly involving calcium, occurring after death. An innovative survey protocol was also applied, focusing on crystal structure characterization by a combination of micro μXRD, XRPD and LA-ICPMS, complemented by the use of focused ion beam scanning electron microscopy. In detail, we investigated the crystallographic signature by the definition of bioapatite cell parameters *a* and *c*, cell volume, crystallinity index and FWHM (Full Width at Half Maximum) of selected diffraction peaks. Rare earth element and other high-field strength element composition was measured to collect any sign of diagenetic footprint, together with paleoecological information. Our results, derived from the study of vertebrate and invertebrate organisms from the Cambrian to the Recent, indicated that fossil bioapatite is characterized by lower values of the cell parameter *a* compared to its modern counterpart, while *c* is less variable, resulting in the general decrease of the bioapatite cell volume passing from living to fossil organisms accompanied by a variability of the crystallinity index influenced by different factors of the organisms when they were living, like the organic matter content.

Acknowledgments: research was undertaken within the PRIN 2022 project BIOVERTICES (BIOdiversity of VERTebrates In the CEnozoic Sea) CUP E53D23021970001.

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Long-term palaeoenvironmental changes from the Late Aptian to Late Cenomanian in the western Tethys: New evidence from the Umbria-Marche Basin (central Italy)

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Keywords: chemostratigraphy, Cretaceous, trace metals

A high-resolution reconstruction of detrital input, chemical weathering, freshwater influx, and palaeoproductivity trends from the late Aptian to the late Cenomanian (~25 Myr) is presented, based on quantitative geochemical data from the Umbria-Marche Basin (central Italy, western Tethys). This record captures a key environmental transition from the multicolored marlstone and black shale-rich sediments of the Marne a Fucoidi Formation to the widespread chalk deposits of the Scaglia Bianca Formation (Gambacorta et al., 2015; Giorgioni et al., 2015).

During the late Aptian "cold snap," oligotrophic surface waters coexisted with oxygenated bottom waters, punctuated by cyclic redox fluctuations recorded in the alternation of reddish and greenish marlstones and marly limestones. Following this cooling phase, a marked warming across the Aptian–Albian boundary was characterized by a dissolution phase and the onset of repeated seafloor deoxygenation cycles. In the early–middle Albian, intensified chemical weathering and increased nutrient supply promoted meso–eutrophic conditions, favoring widespread black shale deposition under stratified surface waters. A major environmental shift occurred during the late Albian, marked by the establishment of stable, arid conditions. These conditions reduced chemical weathering and runoff, leading to oligotrophic surface waters and a persistent thermocline, which lasted until the latest Cenomanian onset of Oceanic Anoxic Event 2 (OAE 2).

The geochemical record documents large-scale climatic-oceanic changes with a transition from an unstable palaeoclimatic–palaeoceanographic regime during the Aptian–Albian to a more stable circulation pattern during the late Albian–Cenomanian.

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The Eocene-Oligocene Transition as witnessed by the fossil record of the Pisco Basin (Peru)

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Keywords: Pisco Basin, Eocene-Oligocene Transition, micropaleontology.

The Eocene-Oligocene Transition (EOT) was characterized by major climatic and ecological changes that marked the passage from the late Eocene warmhouse to the early Oligocene coolhouse world. This study offers a detailed micropalaeontological analysis of the EOT based on calcareous nannofossils, diatoms and silicoflagellates from the upper Eocene to lower Oligocene beds of the Otuma Formation at the localitites of Cerro Tiza and Media Luna, in the Pisco Basin of southern Peru. In the study area, the Otuma strata consist of calcareous siltstones and diatomites that deposited between the Priabonian (37.71-33.9 Ma) and the Rupelian (33.9-27.82 Ma). Average sedimentation rates are estimated at 35.5 m/My and 6.6 m/My at Cerro Tiza and Media Luna, respectively. Diatom assemblages indicate a slight increase in nutrient availability within the basin during the late Eocene and the EOT, but they do not show significant fluctuations, nor they suggest a shift to permanently eutrophic conditions. At Cerro Tiza, calcareous nannofossils disappear during the EOT, whereas they persist at Media Luna. These contrasting responses of phytoplankton assemblages in the two studied sections may reflect variations in the depositional settings of the two localities.

Data-model comparison of the polar warming throughout the Pliensbachian-Toarcian (Early Jurassic)

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Keywords: paleoclimates, Early Jurassic, data-model comparison.

The Pliensbachian-Toarcian transition (Early Jurassic) was a period of major global environmental perturbations, marked among others by the early Toarcian Oceanic Anoxic Event (T-OAE). Overall, this period marks a transition from a late Pliensbachian "Coolhouse" to a Toarcian "Greenhouse" climate. This transition has been mainly studied in strata from the mid-latitude western Tethys. By contrast, the polar latitudes received less attention. Pliensbachian-Toarcian polar environments are of particular interest as several authors hypothesized that cold polar conditions before the T-OAE led to the growth of polar ice caps and permafrost carbon reservoirs, with important implications for the possible causes of major sea-level fluctuations and carbon isotope perturbations recorded across the T-OAE.

We present reconstructions of paleotemperature and local seawater oxygen isotope values ($\delta^{18}O_{sw}$) based on carbonate clumped isotope (Δ_{47}) measurement of well-preserved bivalve shells from Siberia that lived in the Early Jurassic polar arctic seas, covering the late Pliensbachian and early Toarcian. In addition, we compare our estimates to regional temperatures and salinities simulated by the Global Circulation Model (GCM) IPSL-CM5A2 on a Pliensbachian-Toarcian palaeogeography at different atmospheric CO_2 levels. The reconstructed Δ_{47} temperatures suggest near-freezing temperatures (2 to 5°C ± 3°C) during the late Pliensbachian and a warming during the latest Pliensbachian (12.5 ± 3°C) that culminated at the termination of the T-OAE (8 to 18 ± 3°C, mean ~14°C). While the GCM at 6× pre-industrial CO_2 level (PAL) reproduces well the range of late Pliensbachian reconstructed temperatures, doubling the atmospheric CO_2 level in the GCM, as suggested in the literature, struggles to reach reconstructed early Toarcian temperatures. This discrepancy might reflect a potential seasonal bias of bivalve recorded temperatures, or an insufficient polar amplification in the model. Reconstructed $\delta^{18}O_{sw}$ values are all significantly lower than the value of -1 ‰ VSMOW often assumed for the ice-free global Mesozoic oceans, suggesting a substantial influence of freshwater to the hydrological budget of Pliensbachian-Toarcian arctic seas which is in agreement with simulated regional salinities of 20 to 30 in our model runs. Most of the variability of late Pliensbachian $\delta^{18}O_{sw}$ estimates (-8 to -4 ± 1 ‰ VSMOW) can be ascribed to proximal depositional conditions while early Toarcian $\delta^{18}O_{sw}$ values are similar between the different sites (-5 to -2 ± 1 ‰ VSMOW) and indicate higher marine influence during sea-level high stand. The reconstructed changes in both temperatures and hydrologic regimes of polar seas throughout the Pliensbachian-Toarcian global warming and their comparison to climate models point to potential sources of discrepancies between proxy data and models contributing to the improvement of these models to predict future climate changes.

New approaches in metal (stable) isotope geochemistry of bioapatite across time and taxa

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Keywords: bioapatite, metal isotopes, MC-ICPMS.

Recent advances in isotope geochemistry have opened exciting new research avenues for investigating bioapatite ─ the mineral component of bones and teeth ─ as a biogeochemical archive across (evolutionary) time and biological diversity. Innovations in analytical techniques, such as multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) and laser ablation, allow for high-precision and -spatial resolution determination of both radiogenic and stable metal isotopes in vertebrate bioapatite. These developments offer unprecedented insights into diet, mobility, physiology, and environmental interactions of both modern and ancient organisms. When combined with a deeper understanding of isotope fractionation and animal metabolism, these approaches allow researchers to trace back biogeochemical processes with exceptional temporal and taxonomic resolution. They shed light on trophic dynamics, life-histories, climate change adaptation, and evolutionary physiology of extinct vertebrates. This review synthesizes the latest methodological developments and presents key case studies on faunal remains illustrating how metal isotope systems in bioapatite are reshaping our understanding of life's history on Earth.

Tracing the Plio-Pleistocene Transition in a non-marine depositional environment through high-resolution pXRF data: the continental section of Valimi (Greece)

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Keywords: ppt, pXRF, cyclostratigraphy.

The Plio-Pleistocene Transition (PPT) is one of the most interesting periods in recent Earth history. This time interval, between 2.4 and 2.7 Ma, is marked by the most prominent recent "cold" episodes interpreted as the global climatic response to the definitive onset of large and stable ice sheets in the Northern Hemisphere (Lisiecki & Raymo, 2005). In this context, the Lower Group in the Gulf of Corinth (Greece) -and specifically the Valimi Fm.- likely represents the most complete exposure of expanded continental deposits spanning the PPT. Consequently, these deposits provide a unique and almost continuous record of this time interval, and they are very significant for recording climate-triggered landscape transformations (Hemelsdaël et al., 2021).

This study aims to develop a precise age model for the Valimi section in order to chronologically characterize the deposition at the PPT. To achieve this, x-ray fluorescence data were collected along the section with a sampling step of ~ 0.5 m, using a portable XRF device (p-XRF). XRF scanning on the field is fast and provides high-resolution records of relative variations in the elemental composition of sediments, which are very useful in investigating the presence of Milankovitch cyclicity.

A new sedimentary log was created for the section, which was then compared with the previously proposed in other studies. An initial age model (Age Model I) was developed using only paleomagnetic data from Hemelsdaël et al. (2021). Once the initial age model was established, the spatial sequence of the XRF samples was converted into a temporal one, resulting in an XRF time series. These series were then analyzed using the software PAST to identify periodic signals associated with Milankovitch cycles and related climate oscillations. The analysis also highlighted which elemental records best capture the climate signal.

Among the various elemental records, the Ti/Al ratio was selected to construct the second age model (Age Model II), based on the eccentricity cycle signal. This ratio was selected because Ti is typically associated (along with Rb and K) with clay minerals and detrital input (Kylander et al., 2011), while Al is considered a suitable element for normalizing the lithogenic components of sediment against variations in organic content (Löwemark et al., 2011).

The results show that the Ti/Al ratio captured eccentricity signals well and recorded signals related to obliquity and precession. This will make it possible, through future age models, to more precisely frame the climate changes recorded in this section and to gain deeper insight into what the PPT involved in the Mediterranean Basin.

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Millenial scale variability across the Cretaceous/Paleogene boundary event

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Keywords: cyclostratigraphy, K-Pg boundary, millennial-scale climate variability.

The Cretaceous–Paleogene (K-Pg; 66.016 Ma) boundary marks a major extinction event driven by the Chicxulub impact and possibly exacerbated by Deccan Traps volcanism (Hull et al., 2020). Numerical models predict an abrupt "impact winter" (10^1-10^2 yr cooling) followed by longer-term greenhouse warming (10^3-10^4 yr; Hull et al., 2020), but sedimentary and biotic records lack the resolution to test these predictions at millennial scales. Identifying orbital cycles can improve the age control and the resolution of observations on the environmental changes across the K-Pg impact event, yet a millennial-scale chronology of post-impact environmental change remains unavailable.

Here, we present a high-resolution cyclostratigraphy from the expanded Elles I section (El Haria Formation, Tunisia), a proximal-to-shelf succession that preserves a complete, stratigraphically expanded sedimentary succession across the K-Pg boundary. The surveyed succession comprises 5 meters of late Maastrichtian sediments sampled at ~5 cm resolution and 4.1 meters of Danian sediments sampled at ~1 cm resolution. A grain-size record was obtained after chemical disaggregation and washing through a 32 µm sieve. A time-series analysis was conducted on the grain size record by using the Astrochron's timeOpt (Meyers, 2019) and MTM routines, calibrated against La2010b astronomical solutions (Laskar et al., 2011), with Monte Carlo simulations to test the statistical significance. Wavelet and evolutive TimeOpt (eTimeOpt) methods were employed to assess temporal variability of the identified periodical components related to changes in sedimentation rate. Finally, a False-Discovery-Rate correction method was adopted to ensure statistical robustness of detected millennial signals. Bandpass filtering, Hilbert transforms, and bicoherence analysis were eventually applied to assess the potential modulation of high-frequency cycles by orbital forcing and to exclude frequency interactions as a potential source of sub-orbital variability.

Our cyclostratigraphic interpretation offers a crucial tool for a better understanding of post-impact climate dynamics by providing a high-resolution chronology of the timing of biosphere recovery events and environmental evolution after the K-Pg mass extinction.

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Climate, anthropic impact, Anthropocene, and the need for a change in the scientific approach

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Keywords: Anthropocene, sedimentary archives, baseline.

Reconstructing paleoclimate offers several valuable insights, contributing to our understanding of Earth's climate system and its variability over time. It provides a historical perspective on climate change. Studying past climates helps us understand natural climate variability and identify patterns beyond the scope of instrumental records. Then, by establishing a baseline for past climate conditions, paleoclimate reconstructions offer a reference point for assessing the significance of contemporary climate change. This helps in distinguishing between natural and anthropogenic influences on climate.

The concept of the Anthropocene has been widely debated and has led to opposite results: from the denial of a stratigraphic classification to a cornerstone of environmentalist battles. However, we cannot deny that the anthropic impact on the planet can be observed also at the level of the sedimentary record.

A further step requires a pragmatic approach and transversal collaboration. Understanding the anthropic impact and the Anthropocene necessitates analyzing it within the context of Earth system dynamics, a complex and interconnected framework that integrates the geosphere and biosphere. In recent years, the scientific community has intensified efforts to reconstruct the historical footprint of human activities on ecosystems by using a wide range of environmental proxies preserved in natural archives such as marine, lacustrine, and fluvial sediments, as well as to identify suitable markers for the transition to a "Homo sapiens-impacted" world. This baseline is defined not only by geological markers but also by profound changes in biodiversity and ecological systems. Key indicators include biodiversity as well as shifts in ecosystem functions. Integrating these biological and ecological parameters with geological markers provides a comprehensive understanding of this issue.

Finally, addressing the Anthropocene's challenges requires an interdisciplinary approach and opening to soft sciences. In this view, natural sciences diagnose environmental changes, while social sciences explore root causes such as unsustainable consumption, economic inequalities, and governance. Bridging these disciplines is essential for designing equitable and culturally appropriate mitigation strategies.

This presentation aims to strengthen the needed change in paradigm, stressing the concept that future research should not focus on a single aspect but needs collaboration among different disciplines.

Stratigraphic record of the Carnian Pluvial Episode in the Upper Triassic mid-oceanic seamount-type limestone of Kamura, Japan

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Keywords: Late Triassic, Carnian Pluvial Episode, seamount-type limestone.

An abrupt change to a dramatically humid climate occurred during the mid-Carnian (late Julian to early Tuvalian; 234–232 Ma) in the Late Triassic. This enigmatic global event was characterized by a geologically short-lived period of increased precipitation, termed the Carnian Pluvial Episode (CPE). The CPE was associated with a significant input of siliciclastic material into the ocean, which interrupted the growth of carbonate platforms in the Tethys, increased seawater temperatures, and resulted in oxygen-depleted conditions in marginal and deep basins. These extreme events are thought to have been triggered by the volcanism of the Wrangellia Large Igneous Province (LIP) in the Panthalassic Ocean, as well as the Carnian Panthalassic oceanic island basalt volcanism recorded in the Jurassic accretionary complexes of Japan (Tomimatsu et al., 2021, 2023). The Upper Triassic shallow-marine limestones of the Chichibu Belt in Japan, interpreted to have formed on a paleo-seamount in the vicinity of the Wrangellia LIP, may preserve shallow-marine paleoenvironmental records that reflect both the CPE and the volcanism of the Wrangellia LIP. This study examines Upper Triassic limestones from the Kamura section in the Chichibu Belt of central Kyushu, to understand shallow-marine environmental changes in the Panthalassa Ocean during the CPE.

The Kamura section consists mainly of dark-gray to light-gray bedded limestones, ranging in thickness from 30 to 200 cm. Biostratigraphic conodont investigations reveals *Paragondolella* ex gr. *excelsa* (upper Anisian) in the lower part of the section, *Quadralella lobata*, *P*. cf.*polygnathiformis*, and *Carnepigondolella tuvalica* (Julian to Tuvalian) in the middle, and *Epigondolella* and *Mockina* species (Norian) in the upper part. Microfacies analysis reveals that the section is dominated by thin-shelled bivalve and crinoidal wackestone to packstone, deposited in relatively quiet, shallow-marine environments. However, during the Julian, the facies shifted to lithoclastic wackestone to packstone, indicating carbonate redeposition. This was followed in the Tuvalian by non-fossiliferous lime mudstone, reflecting a decline in biodiversity in shallow-marine environments.Organic carbon isotope analysis reveals two negative carbon isotope excursions (NCIEs) during the Julian. A pronounced negative excursion, coinciding with an increase in total organic carbon (TOC), is observed near the Julian–Tuvalian boundary.

Our study shows that the relatively quiet shallow-marine environment on a Panthalassic seamount transitioned into a setting with frequent carbonate redeposition during the Julian. Furthermore, the study section records a rapid decline in biodiversity that occurred at the Julian–Tuvalian boundary, associated with a significant NCIE. The cause of these environmental changes in a relatively stable environment on paleo-seamount during the CPE remains uncertain, and future studies are needed to evaluate possible triggers associated with the Wrangellia LIP volcanism.

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Triple-oxygen isotopes to investigate water-rock interaction in fossil hydrothermal systems

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Keywords: triple-oxygen, hydrothermal, PETM.

Paleoclimatic reconstructions from deep-sea C and O isotopic records have been widely carried out. Minerals formed in hydrothermal systems, instead, constitute an archive for recording continental paleoenvironmental data, providing extra data to oceanic proxies (Dallai & Burgess, 2011). The interaction of rocks with meteoric waters circulating in the system causes an isotopic exchange between the phases: minerals belonging to fossil hydrothermal systems can thus provide information on the isotopic composition of ancient meteoric water. By combining δD-$\delta^{18}O$ data, it is possible to find points of intersection with the Global Meteoric Water Line. However, since the chemical behaviour of oxygen is different from the hydrogen, which can more easily undergo successive exchanges between minerals and fluids, those datasets can lead to biases (Chamberlain et al., 2020). For most natural processes, the ^{17}O fractionation is approximately half than the ^{18}O (mass-dependent fractionation), even though this is not always true: the relationship between $\delta^{17}O$ and $\delta^{18}O$ defines the variable $\Delta^{17}O$ ($\Delta'^{17}O$, linearized), which is used to quantify the deviation from the equilibrium fractionation line (Sharp et al., 2018). The characteristic $\Delta'^{17}O$- $\delta'^{18}O$ space allows to extrapolate the composition of the end-member at infinite w/r of the water-mineral mixing curve. For this reason, the triple oxygen isotopic analysis allows to circumvent the limitations of the assumption of equilibrium and reduces the number of unknowns in the mass balance, making it possible to calculate the isotopic composition of the original water (Herwartz et al., 2015). The research here presented explored the climatic evolution of the Earth during the Paleocene-Eocene transition (c.a 56 My ago), when our planet reached the maximum temperature increasing of the last 100 My, which culminated with the Eocene Climatic Optimum at 50-52 My ago. Arran and Mourne granitic intrusions (Tertiary British Igneous Province, BTIP) formed during the volcanic activity that generated the North Atlantic Igneous Province (NAIP). Quartz and some hydrate minerals, belonging to this area and dated 55-60 My ago, were analyzed by means of the combined IRMS analysis of $\delta^{18}O$, $\delta^{17}O$, and δD, with the aim of reconstructing the isotopic composition of paleo-waters involved in these hydrothermal circuits. Arran granites did not show evidence of a significative water-rock interaction, while Mourne granite showed a clear compositional range, overlapping the GMWL at $\delta^{18}O = -10\pm1$ and representing the meteoric waters of that warm period. The findings of this work suggest the necessity of further studies but demonstrate the efficacy of the combined $\delta^{18}O$, $\delta^{17}O$ and δD analysis for a more detailed and comprehensive understanding of geochemical processes and climate.

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Efficient extraction of radiolarians and conodonts from chert by using dilute NaOH

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Keywords: soda, chert, microfossils.

Radiolarians and conodonts are key microfossils in sedimentary rocks, widely used for palaeontological, biostratigraphic, palaeoenvironmental, and palaeoclimatic reconstructions. Traditionally, their extraction from siliceous rocks, particularly chert (composed of micro- and cryptocrystalline quartz), has relied on hydrofluoric acid (HF) due to its ability to dissolve silica. However, HF is highly corrosive and poses serious health and environmental risks, leading to strict regulatory controls that limit its use in many laboratories and institutions. In response to these challenges, a new method utilizing sodium hydroxide (NaOH) solutions has been developed and tested as a safer and more accessible alternative to HF for extracting radiolarians and conodonts from chert (Rigo et al., 2023; Onoue et al., 2024). Experimental procedures involved treating chert samples with varying NaOH concentrations (1–5 mol/L) at different temperatures (60°C, 80°C, and 100°C) to evaluate the efficiency of silica dissolution and fossil preservation. Results demonstrate that even low-concentration NaOH solutions (e.g., 1 mol/L) heated to 100°C are sufficient to effectively dissolve chert and release well-preserved microfossils. The degree of dissolution was found to be strongly temperature-dependent, with higher temperatures significantly enhancing the solubility of quartz. Notably, the NaOH technique preserves the integrity of microfossils—including radiolarians, conodonts, teeth, and dermal scales—without compromising their mineralogy (e.g., conodonts in biogenic apatite). Compared to the HF method, this approach yields comparable or even superior fossil preservation, enabling clearer morphological identification. In some cases, radiolarians previously unidentifiable to the species level due to fragmentation or corrosion were recovered in near-complete form using the NaOH method. Beyond its scientific utility, the NaOH technique offers significant practical advantages: it is safer to handle, does not fall under international hazardous chemical classifications at low concentrations, and minimizes environmental and health risks. These characteristics make it particularly suitable for use in educational settings, research institutions, and resource exploration facilities where HF use is restricted or prohibited. This method represents a valuable advancement in micropalaeontological methodology, promoting broader access to high-quality fossil extraction from siliceous sediments and supporting sustainable practices in geoscientific research.

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Bulk and clay mineralogy from the Middle Eocene Climatic Optimum (MECO, ~40 Ma) at the Neo-Tethyan Alano Section (northeastern Italy): negative or positive climate feedback?

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Keywords: MECO, paleoclimate, clay mineralogy.

The middle Eocene was characterized by a long-term global cooling trend, interrupted by a distinct warming event lasting approximately 500 kyr—the Middle Eocene Climatic Optimum (MECO, ~40 Ma). This interval was marked by a 4–6°C increase in surface and deep ocean temperatures, along with a transient rise in atmospheric pCO_2 (Bohaty et al., 2003). The MECO has gained increasing scientific attention, as it may represent a past analogue for future climate trajectories under continued anthropogenic greenhouse gas emissions. Continental weathering played a crucial role during such warm phases by removing atmospheric CO_2 through silicate hydrolysis. At the same time, reverse weathering—a process involving the formation of authigenic clays that releases CO_2—has recently been proposed as a mechanism that could prolong elevated CO_2 levels during the MECO (Krause et al., 2023). Analyzing clay and bulk mineralogy in sedimentary archives provides valuable insight into these processes. The composition and preservation of clay minerals help reconstruct the conditions in which they formed, offering clues about continental weathering and potential marine authigenic reactions. Despite its importance, the mineralogical record of the MECO remains underexplored. This study applies an integrated approach combining bulk and clay mineralogy from the upper Bartonian-lower Priabonian expanded Alano di Piave section (northeastern Italy), a bathyal Neo-Tethyan site designated GSSP of the Priabonian (Agnini et al., 2021). This section offers a continuous and well-preserved archive of the MECO, tightly constrained by stable isotope records, making it ideal for investigating paleoclimatic and paleoenvironmental dynamics. The observed mineralogical changes reflect the regional imprint of MECO-related climatic shifts. Moreover, the reconstructed weathering regimes provide context for the marked biotic changes reported from this section. Our results show that changes in clay mineral composition across four distinct phases—initial conditions, perturbation, recovery, and stabilization—suggest a transition from physical to chemical weathering during the MECO. However, we found no evidence of reverse weathering or authigenic clay formation at the Alano section, suggesting that this mechanism may not have played a regionally significant role in sustaining the late MECO warming.

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A multidisciplinary approach to the "lastame" vertebrate *Lagerstätte* (Upper Cretaceous, Veneto region)

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Keywords: calcareous plankton, stable isotopes, Turonian.

The "lastame" is a nodular lithofacies of the Upper Cretaceous Scaglia Rossa Veneta, found in the Lessini Mountains (Veneto region, northeastern Italy). This lithofacies has preserved skeletal remains of marine vertebrates, including chondrichthyans, marine turtles, and mosasaurs, which have recently gained international recognition (Long, 2024). This study aims to establish the biostratigraphic framework of the "lastame" and its vertebrate fossils using a multidisciplinary approach. Biostratigraphy is based on calcareous nannofossil and planktonic foraminiferal assemblages from a reference section at a quarry near Breonio (Verona, Lessini Mountains). Additionally, stable isotope analyses are employed to correlate the deposition of the "lastame" with the Turonian (Late Cretaceous) carbon cycle and climatic events. Specifically, the calcareous plankton assemblage, characterized by the first occurrences of *Eiffellithus eximius* s.s. and *Lucianorhabdus maleformis*, along with the absence of *Dicarinella concavata*, allows for a late Turonian age assignment for the "lastame". The "lastame" chondrichthyan assemblage is also discussed and compared to coeval assemblages from the Tethyan and Atlantic domains. Notably, the chondrichthyan assemblage bears closer similarities to those of the Saxonian and Bohemian regions than to other assemblages, yet shows a tropical affinity, evidenced by the presence of the sclerorhynchiform *Onchosaurus*. The accumulation of vertebrate fossils in this interval, despite the generally low density of macrofossils in the Scaglia Rossa, may be related to eutrophic conditions in the water column, as suggested by the occurrence of frequent calcareous dinocysts (calcispheres), which could have supported a more diverse and abundant vertebrate assemblage compared to oligotrophic environments.

Long J. (2024) - The Secret History of Sharks: The Rise of the Ocean's Most Fearsome Predators. Ballantine Books, 480 pp.

Calcareous plankton biostratigraphy and carbon cycle events across the Late Cenomanian to Early Coniacian in the Tethyan region

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Keywords: Cretaceous calcareous plankton, stable isotopes, biostratigraphy.

The Turonian, following the late Cenomanian greenhouse peak of the Oceanic Anoxic Event 2 (OAE2), is characterized by a cooling trend marked by several cooling phases, culminating in the so-called "Late Turonian Cool Phase" (Wiese & Voigt, 2002; Jarvis et al., 2015). These paleoenvironmental changes significantly impacted the trophic network, particularly affecting primary producers such as calcareous plankton, and led to an evolutionary turnover (e.g., Leckie et al., 2002; Erba, 2004). However, the correlation of the paleoclimatic and paleoenvironmental frameworks of this interval remains relatively poorly understood, mainly due to uncertainties regarding the reliability and synchronicity of some major events used for biostratigraphic and chronological correlations. To address these biochronological ambiguities and refine the stratigraphic framework, we present a new integrated calcareous plankton biostratigraphy for the latest Cenomanian to earliest Coniacian interval, based on data from the Quero section (Belluno Basin, northeastern Italy) and the Bottaccione section (Umbria-Marche Basin, central Italy). Several bioevents currently used in zonal schemes were identified. The bulk carbonate $\delta^{13}C$ record from the Quero section reveals five major positive carbon isotope excursions, which have been correlated with known events recorded in the English Chalk, although a possible hiatus at the base of a nodular layer at Quero cannot be ruled out. These same events are also recognizable in the $\delta^{13}C$ profile from Bottaccione. Comparing the relative position of bioevents as occurring in the $\delta^{13}C$ curve in multiple locations enabled us to disentangle the reliability of calcareous plankton biohorizons. In addition, our analysis suggests that distinguishing between rare and common occurrences of taxa enhances the potential number of biohorizons for biostratigraphic purposes. The results indicate that only a limited number of biohorizons are reliable for correlation. Furthermore, our study emphasizes the importance of employing constrained taxonomic characters combined with semi-quantitative analytical methods, which help to dispel the notion of diachronism affecting taxa such as *Eiffellithus eximius* and *Micula*.

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From continental clastics to carbonate platforms: tracing climate and basin evolution in the Ligurian Briançonnais during the Permian-Triassic transition

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Keywords: carbonate platforms, Permian-Triassic, palaeoclimate.

The Triassic period played a fundamental role in shaping the Ligurian Briançonnais domain within the Western Alps, driving the transition from siliciclastic to carbonate deposition inside wide extensional basins formed between the late Variscan (Late Carboniferous–Early Permian) and the Alpine (Late Triassic?–Oligocene) orogenic cycles.

Literature data suggest that sedimentation commenced in the Lopingian?, initially marked by widespread continental clastics (Quarziti di Ponte di Nava Fm.), originating from the erosion of potassium-alkaline volcanic rocks (e.g. Porfiroidi del Melogno Fm.) (Boni et al., 1971; Cabella et al., 1988; Cortesogno et al., 1982; Dallagiovanna et al., 2009). These alluvial plain deposits progressively evolved into shallow-water carbonate sedimentation, responding to marine ingression and persistent extensional tectonics.

This study adopts a multidisciplinary approach, integrating sedimentological, stratigraphic, and paleontological data to reconstruct the paleoenvironmental and paleoclimatic framework of the region. The recent discovery of vertebrate footprints, combined with extensive geological survey data in the Ormea and Albenga areas (CARG sheets n. 244 and 245), offers valuable insights into the terrestrial and coastal ecosystem dynamics preceding the establishment of the Middle Triassic carbonate platform. These studies refine the timing of sediment emplacement and reveal critical climatic fluctuations that may have influenced local biodiversity and depositional processes.

By establishing a detailed regional correlation, this research provides a comparative analysis between different sectors of the Briançonnais domain s.l. through the Western Alps. This broader perspective enhances our understanding of the long-debated role of protracted extensional tectonics between the end of the Variscan orogenesis and the start of the Alpine cycle, highlighting its implications for paleoenvironmental transformations during the Triassic.

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The Significance and Early Record of Siphonodella in the Devonian of Holy Cross Mountains

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Keywords: conodont, elements, Devonian.

The *Siphonodella* lineage is the most successful group of conodonts that underwent rapid radiation in the Early Carboniferous and became a major biostratigraphic tool. Although the *Siphonodella* genus has crucial importance for age correlation of the earliest Carboniferous strata, its importance, for good reasons, was reduced for the latest Devonian (Spalletta et al., 2017).

The main reason for the critical approach to this marker is its scarce record in the end-Devonian and the unclear differentiation between two transitional species, *S. praesulcata* and *S. sulcata* (Kaiser & Corradini 2011). On top of all this, the origin of this lineage and where it comes from still remain unclear.

Due to the absence of natural assemblages or clusters, the composition of the *Siphonodella* apparatus, significant to tracing its evolutionary roots, has been subject to debate. Sandberg et al. (1978) suggested that *Elictognathus lacerata* was the P_2 element of *Siphonodella*, whereas *Dinodus leptus* represents the remaining elements of the apparatus. An evident problem with this hypothesis was the lack of either *Elictognathus* or *Dinodus* in the Devonian record. However, the abundant and dense sample from the latest Devonian of Kowala in the Holy Cross Mountains provided both of these element types (Świś & Dzik 2021).

The most interesting feature of Devonian *Dinodus* is that they seem far more specialised and unusual than the more advanced Carboniferous members, while Devonian platformless *Elictognathus* seems underdeveloped. This data will be supplemented with *Siphonodella* and *Dinodus* elements from older beds of Kowala, among which is the earliest *Dinodus*-type element and a singular element with a *Siphonodella*-like aboral side and probably convergently developed rostral ridges, which are features of advanced Siphonodellids. It shows that the Siphonodellids of the Late Devonian are a more diverse and interesting group.

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Biotic and abiotic interactions in salt crusts of Ntwetwe Pan (Botswana): implications for biosignature preservation in arid, hypersaline environments

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Keywords: arid environments, biomineralization, biosignatures.

This study investigates the evaporitic crusts of Ntwetwe Pan, a salt pan within the Makgadikgadi Basin in Botswana, which is subject to extreme physicochemical conditions, including hypersalinity, high alkalinity, and seasonal desiccation. The region lies in a semi-arid climatic zone, characterized by low annual rainfall (~300 mm/year) mostly confined to the austral summer months (November to March), and prolonged dry seasons with high evaporation rates that promote intense evaporitic activity. Surface water inputs occur through ephemeral rivers draining the surrounding highlands, with occasional inflow from the Boteti River during exceptionally wet years. In the dry season (April–October), the pan surface becomes exposed to wind erosion and widespread evaporite formation. The aim of this study is to characterize the microtexture and mineralogical composition of surficial salt crusts and to assess the interplay between abiotic evaporitic processes and microbial mineralization. Ten surficial salt-crust samples were collected along a 280 m transect from the shoreline to the pan's center. Multiparameter profiling revealed consistently alkaline pH values and highly heterogeneous electrical conductivity, ranging from ~1,000 µS/cm at the margin to 200,000 µS/cm mid-pan, reflecting uneven salinity gradient driven by spatially variable evaporation. X-ray diffraction (XRD) confirmed halite as the dominant phase, with calcite and quartz ubiquitous, and thenardite and trona in samples from higher-salinity areas. Scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDS) uncovered a complex microfabric of abiotic crystals, interwoven filaments, and EPS-like matrices suggestive of biosignatures. Two main filament types were observed: thick, mineral-encrusted "armored" filaments in moderately saline zones, and thin, collapsed or dispersed ones—some resembling sheathed bacteria—in highly saline areas. Additionally, needle-shaped crystals and porous morphologies were observed particularly in samples from intermediate salinity zones. These findings indicate a correlation between salinity gradients and filament

morphotypes: EPS-mediated precipitation promotes mineralization under moderate salinity, while osmotic stress may drive filament collapse or EPS encapsulation at higher salinities. Porous and needle-shaped morphologies are likely abiotic and highlight the need for caution when interpreting such structures as biosignatures.

The observed association between microbially influenced textures and seasonal evaporitic processes underscores the importance of climate-driven hydrological cycles on the preservation potential of biosignatures. The Makgadikgadi Pans thus offer a valuable analogue system not only for planetary science but also for understanding microbial survival and preservation in terrestrial hypersaline environments under arid climatic regimes.

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Brachiopod shell sclerochemical record of seasonality variations across the late Tournaisian-Moscovian phases of the Late Palaeozoic Ice Age

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Keywords: brachiopods, late Palaeozoic, seasonality.

Sclerochemical analyses ($\delta^{18}O$, $\delta^{13}C$) of fossil shells allow to obtain high-resolution data that provide valuable insights into past climatic changes, especially at seasonal scale. Rhynchonelliformean brachiopods, with their low-Mg calcite shells, have proven to be reliable bioarchives for seasonal reconstructions of seawater temperatures both in the recent and distant past (Angiolini et al., 2012; Crippa et al., 2025; Viaretti et al., 2025). They were particularly abundant during the late Palaeozoic, a time interval which recorded dramatic climatic changes, from the Late Palaeozoic Ice Age (LPIA) to the end-Permian hothouse.

Here, we present preliminary data from sclerochemical analyses of diagenetically-screened brachiopod shells collected from the Alborz Mountains in North Iran (Mobarak, Dozdehband and Qezelqaleh formations), Central Iran (Jandaq Formation) and Guizhou Province in South China (Baizuo Formation). These specimens, belonging to different species of the classes Strophomenata and Rhynchonellata, are stratigraphically distributed from the upper Tournaisian to the Moscovian, bracketing the first phases of the LPIA across the Visean-Serpukhovian interval and the phases of glacial expansion around the Mississippian-Pennsylvanian boundary and the early Moscovian (Montañez, 2020). The Iranian fossil localities were located at a palaeolatitude from 40°S in the Mississippian to 30°S in the Pennsylvanian, while during the same interval the South China Block was located at a palaeolatitude of 0-20°S. They thus provide a robust record of the biotic response to climate change at different paleolatitudes.

Our preliminary results record an increase in seasonality (testified by a $\Delta\delta^{18}O$ value passing from ~1‰ to ~2‰) from the Visean to the Serpukhovian-early Moscovian, while the average $\delta^{18}O$ value is increasing as well along this time span. These results indicate progressively cooler climate conditions, up to the peak of the LPIA (Montañez, 2020). Instead, during the middle Moscovian brachiopod shells record a lower seasonality ($\Delta\delta^{18}O$ ~1‰) along with a lower average $\delta^{18}O$ value, which could indicate a possible interglacial phase in the mid-Pennsylvanian, although further investigation is needed. The observed differences in the average $\delta^{18}O$ values between shells from the Carboniferous of Iran and South China possibly reflect latitudinal variations in the $\delta^{18}O$ value of the seawater. On the other hand, the shells from the upper Tournaisian record very low $\delta^{18}O$ values, between –3‰ and –8‰, and oscillating profile likely reflecting a seasonal pattern. Since the shells are well-preserved, these values remain enigmatic and spark questions on the Tournaisian climate and ocean chemistry.

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S17.

Unraveling the interplay of climate and human pressure during the Holocene in alluvial and marine archives

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Integrated reconstruction of paleoenvironmental conditions and interactions with ancient population in the northernmost Adriatic lagoons during the Holocene

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Keywords: palynology, lagoon, NE Italy.

In the north-western Adriatic the transitional environments connecting the alluvial plain to the coast have changed significantly during the last 8000 years in relation to the sea-level rise occurred after the LGM (Last Glacial Maximum). Specifically, the combined influence of marine and riverine processes has deeply modified the coastal plain morphology and its resources, thus inducing significant consequences on the ancient settlement dynamics. The research focused on key areas in the coastal plain east of Venice, especially along the lagoons of Grado-Marano and Caorle, which represent the northernmost brackish environments in the Mediterranean.

Archaeological traces are often available at surface or at shallow depth and the combined study of LiDAR-derived DEMs and aerial photographs, stratigraphic boreholes, XRF core-scanner analysis and proxies such as pollen and microfossils (i.e. foraminifera assemblages) allows for a detailed paleoenvironmental reconstruction and estimation of past sea-level variations, as well as an assessment of the ancient human impact on the transitional environments.

New data from stratigraphic core in Torviscosa (TOR), just a few kilometres west of Aquileia, demonstrate that RSL in the area was around -6.5 m MSL at about 3500 BCE. While the evolution of foraminifera assemblages throughout the core describes a progressive sea-level rise, pollen data allows, for the first time, the detection and quantification of the wood clearance that occurred in the distal plain during the Middle Bronze Age. This data agrees with recent investigations carried out in Udine, where at the beginning of the Recent Bronze Age the construction of a mega mound largely sealed the former soil of the settlement. In this ancient buried surface the paleobotanic data showed a significant anthropogenic impact already during the Middle Bronze Age (Fontana et al., 2023).

Another area of interest is in Bibione, near the present-day delta of Tagliamento River, where a long tract of a relict coastline hosting the Roman coastal villa of the Mutteron dei Frati has recently been investigated. Paleoenvironmental reconstructions rely on several hundreds of manual boreholes and some mechanical deep cores for calibration. The new data allow to reconstruct in detail the extension of the eastern sector of the Caorle Lagoon during the Roman period and to characterize for some kilometres a major tidal inlet related to a tidal mouth, that around the 3rd century BCE reached a depth of 25 m. The ancient human interaction with the tidal processes is documented in the infill of the tidal mouth by the presence of centimetric brick debris already from the bottom of the channel. Moreover, the pollen analyses testify the impact of cultivation on the vegetation since the first Roman occupation of the zone.

Fontana A. et al. (2023) - The largest prehistoric mound in Europe is the Bronze-Age Hill of Udine (Italy) and legend linked its origin to Attila the Hun. Scientific Reports, 13, 8848, https://doi.org/10.1038/s41598-023-35175-8.

Geochemical and isotopic fingerprints of Po and Adige River sediments and the paleohydrography of the Southern Venetian Plain

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Keywords: isotopes, sediments, Veneto region.

This study presents a multi-proxy geochemical and isotopic investigation on Holocene alluvial sediments from the easternmost Po Valley (NE Italy), an area influenced by overlapping depositional systems of the Po and Adige Rivers. A subset of samples, previously characterized via X-ray fluorescence (XRF) and geochemically classified according to Natali & Bianchini (2017), was further analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Thermal Ionization Mass Spectrometry (TIMS) to determine trace element composition and Sr-Pb isotope ratios. ICP-MS results show reduced dispersion and enhanced consistency compared to XRF data, improving sediment provenance attribution. $^{87}Sr/^{86}Sr$ and $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ isotopic data corroborate these findings and indicate sediment sources consistent with Alpine ore deposits: western Alps for Po-related sediments and Southalpine regions for Adige-related ones.

Complementing this inorganic dataset, the study also explores the C, N, and S elemental and isotopic compositions of the same sediment suite through elemental analyzer coupled with isotope ratio mass spectrometry (EA-IRMS). $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ signatures reveal distinct differences between Po and Adige source areas. These differences are not attributable to anthropogenic inputs or fertilization practices but rather reflect natural biogeochemical processes conditions within the respective catchments. For instance, $\delta^{13}C$ in organic carbon is influenced by the relative presence of C_3 and C_4 plant material, while $\delta^{13}C$ in inorganic carbon distinguishes between lithogenic and pedogenic carbonates. The nitrogen and sulfur isotopic variations are linked to differences in organic matter cycling, soil maturity, and basin hydrology for example Po sediments being older and sourced from a larger, more mature drainage basin exhibit higher S isotopic ratio than those of Adige.

Integration of trace element and isotope data enabled the reclassification of some sediment in the Adige and Po systems and revealing also the presence of a Po river paleo-channel. These findings improve regional discrimination of fluvial inputs and demonstrate that the carbon, sulphur, nitrogen, strontium, and lead isotopic dataset serves as an additional provenance tool. The natural isotopic variability described here also provides an essential geochemical background for environmental monitoring, aiding in the identification of future anthropogenic anomalies.

Natali C. & Bianchini G. (2017) - Geochemical proxies of sediment provenance in alluvial plains with interfering fluvial systems: A study case from NE Italy. Catena, 157, 67-74, https://doi.org/10.1016/j.catena.2017.05.018.

Lakes and swampy areas in alluvial plain, a long tale of nature and man interaction: the lake of Sesto case History (Central Italy)

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Keywords: climate change, terrestrial archive, Bientina area.

Alluvial and coastal plains form and evolves under different natural forcings like climate, tectonic and sea level rise. Since the development of the agricultural practices progressively agricultural activity focused on alluvial plain and human activity was one of the main drivers competing with the natural evolution of the alluvial plain. In the Mediterranean basin many alluvial plains were characterized in different stages of the development of shallow lacustrine and/or important swampy area. In Italy most of the shallow lacustrine with have been reclaimed since the roman time. To reconstruct the story of these shallow lacustrine system is fundamental because many of these areas are important hot spot of biodiversity and their preservation and/or restoration can be strategic. In this work we present the Late Holocene evolution of Sesto Lake (central Italy) based on chronological, stratigraphic, geomorphological, geoacheological, biological (pollens) data. In the context of fluvial environment (Bini et al., 2025), the lake started to evolve in the LALIA (Late Antique Little Ice Age), a phase of climatic deterioration locally characterized by an increasing precipitation (Zanchetta et al., 2020). The high resolution of the data analyzed allows the reconstruction of Human- environment relation in the last thousand years until the final lake reclamation at the end of the 19thcentury.

Bini M. et al. (2025) - The Paleo-Serchio River: history of floods between Lucca and Pisa during the Roman period. Journal of Quaternary Science, 40, 141-152.

Zanchetta G. et al. (2021) - Beyond one-way determinism: San Frediano's miracle and climate change in Central and Northern Italy in late antiquity. Climatic Change, 165(1-2), 1-21.

Reconstructing Holocene climate variability in the North Ionian Basin using a multiproxy approach

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Keywords: calcareus nannoplankton, rapid climate changes, North Atlantic Oscillation.

To improve understanding of Holocene paleoclimate variability in the Central Mediterranean, we present new data from sediment core ND14Mbis (Bronzo et al., 2025), collected from the North Ionian Basin at 665 m depth during the NEXTDATA2014 cruise, aboard R/V Urania (CNR). A multiproxy approach was used, integrating micropaleontological, isotopic, and XRF core scanner data to assess climate variability on millennial to centennial scales. We analysed 132 cm of greyish hemipelagic sediments from the 332 cm-long ND14Mbis core. The Bayesian age model, based on ten ^{14}C measurements, is from Checa et al. (2020). The dataset includes calcareous nannofossil assemblages, $\delta^{18}O$ and $\delta^{13}C$ from *Globigerinoides ruber* white, and XRF-derived Ca/Al and K/Al ratios. Results were combined with existing data from the same core of planktic foraminifera (Checa et al., 2020) and nannofossils (Cascella et al., 2021) focused on the Sapropel 1 (S1) interval. A hierarchical cluster analysis was performed on the total calcareous nannofossil assemblage, excluding reworked coccoliths. Also, a wavelet analysis on cold water calcareous nannofossil taxa was conducted, revealing a 1.6 ky periodicity consistent with the 1.5 ka North Atlantic Bond cycles.

High-resolution analysis allowed the identification of major climatic phases, including the late African Humid Period (AHP, 10–5.4 ky BP), during which S1 (10–6.6 ky BP) was deposited, and Pre-Roman (4.1–2 ky BP), Roman (2–1.5 ky BP), and Post-Roman (1.5–0 ky BP) cultural periods. During S1, dysoxic bottom waters were interrupted by brief cooling at 8.2 and 7.4 ky BP. Following S1's end, $\delta^{18}O$ heavier values evidence renewed Adriatic Deep Water formation. At the same time, lower $\delta^{13}C$ and elevated K/Al ratios suggested stronger Po River influence. After 5.4 ky BP, a transition toward drier conditions marked the AHP's end, evidenced by decreases of continental runoff proxies, such as abundances of reworked coccoliths and *Syracosphaera pulchra*, and $\delta^{13}C$ and K/Al values. Around 4.2 ky BP, a major climate reorganisation occurred, likely tied to a stronger North Atlantic Oscillation (NAO) influence. This transition is supported by nannofossil data and XRF trends, indicating that a negative NAO index drove an increase in holococcolith abundance and elevated K/Al ratios. Afterwards, short-lived events were recorded throughout the later Holocene, with nannofossils proving to be particularly responsive to cooling phases.

During the Little Ice Age (0.5–0.3 ky BP), an increase in warm-water species coincided with reduced coccolithophore productivity, likely linked to enhanced river runoff and water column stratification. This pattern is corroborated by reworked coccoliths and elemental data, and mirrors trends seen in the South Adriatic Basin (Cascella et al., 2019).

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Bronzo L. et al. (2025) - Holocene paleoclimatic evolution in the North Ionian Basin of the Mediterranean Sea: A multiproxy approach. Palaeog., Palaeocl., Palaeoecol., 671, 112977, https://doi.org/10.1016/j.palaeo.2025.112977.

Cascella A. et al. (2019) - Climate variability of the last ~2700 years in the Southern Adriatic Sea: coccolithophore evidences. Holocene, 30(1), 53-64, https://doi.org/10.1177/0959683619865600.

Cascella A. et al. (2021) - The response of calcareous plankton to the Sapropel S1 interval in North Ionian Sea. Glob. Planet. Chang., 205, https://doi.org/10.1016/j.gloplacha.2021.103599.

Checa H. et al. (2020) - High resolution paleo-environmental changes during the sapropel 1 in the North Ionian Sea, Central Mediterranean. Holocene, 30(11), 1504-1515, https://doi.org/10.1177/0959683620941095.

Distribution and transportation of polycyclic aromatic hydrocarbons (PAHs) at the Tonnarella torrent mouth in the Gulf of Naples (Italy)

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Keywords: hydrocarbons, rainfall, marine.

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds mainly linked to anthropogenic activity and recognized as toxic to humans and the environment. However, PAHs can rised also from natural causes (petrogenesis and biogenesis processes). In highly urbanized areas, large quantities of PAHs in the environment are linked to industrial activities and above all to vehicular traffic. Due to their chemical-physical properties, PAHs are mainly transported and circulated in the environment through fine-grained particulate matter and sediment. From the streets, therefore, with the run-off of the first rain waters, they end up in the natural drainage basins and up to the mouth into the sea, where they are deposited together with the sediment (Wu et al., 2003; Stokes et al., 2006; Mali et al., 2022). Five seabed sediment stations at the mouth of the Tonnarella torrent (Sorrento Peninsula), in the Gulf of Naples, were monitored in the period 2018/2019 with two sampling campaigns, the last one corresponding with an exceptionally large rainfall event after the dry period of the summer season. The analytical data relating to PAHs and metals, associated with organic matter and grain size, for this campaign reveals a sediment with a greater pelitic component and a notable increase in the values of Benzo (a) pyrene, which are also associated with significant increases in some heavy metals, Pb and Cr. The first rain waters on the ground and their convergence towards the natural impluvium of the Tonnarella torrent represent the vehicle for transporting dust and particulate matter, and with them heavy metals, PAHs and organic substances, accumulated during the dry summer period with intense vehicular traffic. At the mouth, the mud transported by the stream, which under the effect of an exceptional rainfall event has assumed the flow rate of a torrent, tends to settle on the seabed and to retain all the pollutants (Liu et al., 2014).

Liu F. et al. (2014) - Distribution and transportation of polycyclic aromatic hydrocarbons (PAHs) at the Humen River mouth in the Pearl River delta and their influencing factors. Marine Pollution Bulettin, 84(1-2), 401-410, https://doi.org/10.1016/j.marpolbul.2014.04.045.

Mali M. et al. (2022) - Improved identification of pollution source attribution by using PAH ratios combined with multivariate statistics. Sci. Rep., 12, 19298, https://doi.org/10.1038/s41598-022-23966-4.

Stokes J.D. et al. (2006) - Behavior and assessment of bioavailability of organic contaminants in soil: relevance for risk assessment and remediation. Soil Use and Management, 21(12), https://doi.org/10.1079/SUM2005347.

Wu Y. et al. (2003) - Polycyclic aromatic hydrocarbons in the sediments of the Yalu Jiang estuary, North China. Mar. Pollut. Bull., 46(7), https://doi.org/10.1016/S0025-326X(03)00035-3.

High-resolution pollen and multi-proxy analysis to reconstruct paleo depositional events from a stratigraphically expanded Holocene succession (Po Delta, Italy)

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Keywords: pollen, Holocene, Po delta.

This study explores the potential of fossil pollen as an additional proxy for characterizing paleo-depositional events (e.g. river floods, storms) at the land-sea transition, while also focusing on environmental and climatic changes during the recorded Holocene period. For this purpose, a multi-proxy approach combined with high-resolution palynological analysis (97 samples) was applied to borehole S1P, drilled 40 m deep into the Po della Pila delta. Compositional (e.g. SEM, and XRF-scanning) and paleontological (e.g. meiofauna) analyses were performed to refine sedimentary facies interpretation. Chronological data from core S1P reveal a stratigraphically expanded and well-preserved archive spanning the Holocene. 7 AMS ^{14}C dates were obtained from the bottom of the core up to a depth of 22 meters, returning ages from approximately 10 kyrs BP to 6.5 kyrs BP. A subsequent chronological gap suggests the presence of a hiatus or condensed interval, followed by a potentially continuous and expanded sequence from the Roman period to the present, confirmed by a radiocarbon age reporting 83-262 CE. Finally, ^{210}Pb equilibrium at 5.24 m depth confirmed the record of the last ~100 years of sedimentation in the top core meters. The bottom core section (approx. 40-31 m depth) consists mostly of fine-grained, organic-rich strata accumulated away from a direct fluvial input, as documented by high peaks in pollen grain concentration and by the occurrence of a typical infralittoral meiofauna. Around 35 m depth an increase in river input is recorded by a generally lower concentration of pollen grains and a change in the foraminiferal communities that display the partial replacement of sensitive taxa by opportunistic taxa preferring OM-enriched substrate; it is also observed a consequent slight increase of reworked pollen grains, which becomes even more noticeable from 30 m onwards. Upsection, stacked mud beds and thicker fine sand layers form a coarsening-upward, river-dominated succession, 25 m thick, that was deposited during the last centuries. Pollen is poorly preserved and reworked, and the meiofauna is either scarce or absent. Collectively, these features suggest a high-energy depositional environment linked to fast delta lobe progradation and prodelta to delta-front transition, where pollen concentrations are at their lowest. In the uppermost 6 m, organic-rich muds are intercalated with silt and fine sand layers and contain numerous wood fragments and scattered valves of brackish ostracods, indicating the onset of the modern delta plain environment, which is corroborated by peaks in hygrophytes plants. This study shows the potential of deltaic strata as reliable sedimentary archives for reconstructing past precipitation intensity and vegetation changes. In addition, it provides a high-resolution reconstruction of Late Holocene environmental and climatic changes, through the integrated analysis of pollen and other proxy.

Geogenic and anthropogenic geochemical associations of elements in alluvial sediments and suspended particulate matter as indicators of anthropogenic elemental anomalies in an Alpine river – case study of the Mura River, Austria and Slovenia

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Keywords: river sediments, geochemical associations, potentially toxic elements.

The geochemical properties of alluvial sediments in an area characterized by a complex natural and anthropogenic environment were investigated using the example of the transboundary Alpine Mura River (Austria, Slovenia, EU). A total of 65 sediment samples from the active river channel and tributaries and 59 samples from 6 floodplain alluvial sediment profiles were collected and analyzed by ICP-MS after multi-acid digestion (HNO3, HClO4, HF, HCl) in order to determine the elemental composition. Factor analysis revealed four natural geochemical associations (K–Ba–Rb–Ga–Li–Tl–Cs–Be–Al–Cu–V; Th–YREE–U; Zr–Hf–Nb; Na–Sr), one anthropogenic association (Cd–In–Zn–Pb) and two combined (geogenic and anthropogenic) associations (Ni–Cr–Mg–Co–V and Fe–Sc–Ti–Nb) (Čeplak et al., 2025). To gain a comprehensive insight into geochemical fluvial processes, suspended particulate matter (SPM) was further investigated. Forty-one samples were taken from the main channel as well as 25 from tributaries and analyzed using ICP-MS after complete digestion using HNO3 and H_2O_2. A cluster analysis revealed two natural (Sr–Ca; Al–Ba–Ga–K–Li) and two combined (geogenic and anthropogenic) associations (Co–Fe–Mg–Ti–V–YREE; Bi–Cd–Cr–Cu–Mn–Ni–Pb), which generally correspond to the geochemical associations of stream and floodplain sediments. It has been found that the geochemical associations in the stream and alluvial sediments mainly reflect the natural processes in the catchment related to erosion and weathering and reflect the locations of ore mineralization, which are particularly characteristic of the upper part of the catchment. In contrast, the concentrations of most elements in SPM predominate in the lower part of the catchment compared to the upper part, showing increased material erosion and transport in the lower part of the river. In addition, the SPM samples are more susceptible to anthropogenic impacts; elevated levels of potentially toxic elements (PTE) have been detected in urban areas and in locations downstream of urban centers. In summary, SPM could serve as an useful indicator for the investigation of anthropogenic influences in fluvial systems.

Čeplak B. et al. (2025) - Understanding the geochemical composition of alluvial sediments in a complex environmental system – A case study of the Mura/Mur river. Catena, 249, 108605, https://doi.org/10.1016/j.catena.2024.108605.

The real structure of the so called "4.2 event": novel $\delta^{18}O$-$\delta^{13}C$ speleothem data from Sardinia (Italy, Western Mediterranean)

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Keywords: 4.2 event, Holocene, paleoclimate.

The Holocene is characterized by a multitude of climatic oscillations and the Mediterranean region serves as a significant area for exploring such climate variability due to its geographical position and diverse geological, geomorphological and orographic features. Among several Holocene climate instabilities, the "4.2 event" holds particular significance. Identified as one of the most cooling/drying episodes, it is widely recognized as a "megadrought" and as a key factor in the decline of ancient civilizations. However, the nature of the event is at times elusive, as it is not recorded in some sites and appears to be out of sequence in others. Therefore, a more detailed investigation of the supposed 4.2 is needed, possibly with a multiproxy approach and from understudied regions, in order to better understand the timing of this change, collocated at 4.2 ka, but it might be spread over a broader interval. The aim of this study is to present novel multiproxy data ($\delta^{18}O$-$\delta^{13}C$, fabric and the trace elements), obtained from a carbonate stalagmite (SARM2) collected in the S'Armidda Cave (Sardinia, Italy, Western Mediterranean). U-Th based chronology of SARM2 indicates that the speleothem deposition occurred between 5.6±0.14 to 3.3±0.14 ka. The average proxy chronological resolution is about 16 years. Due to the cave's geographical location, the $\delta^{18}O$-climatic signal of SARM2 is primarily interpreted as reflecting the rainfall amount (amount effect), while $\delta^{13}C$ is associated with vegetation activity. Preliminarily $\delta^{18}O$-$\delta^{13}C$ data attest that at ca. 4.7 ka, a centennial long deterioration of climate occurred, characterized by reduced rainfall and vegetation activity. While SARM2 is mostly composed of calcite, an evident aragonite layer is present during this period, suggesting particularly dry conditions. From ca. 4.6 ka, $\delta^{18}O$ and $\delta^{13}C$ values indicate an increase in rainfall, that peaks at ca. 4.35 ka. Progressing toward 4.2 ka, another phase of climate deterioration is observed, although of lesser magnitude compared to the event at 4.7 ka, as evidenced by the absence of aragonitic. After 4.2 ka, $\delta^{18}O$ and $\delta^{13}C$ decouple, suggesting stable rainfall conditions but increased vegetation activity. Contrary to previous interpretations that represented the 4.2 event as a single, continuous dry period, our findings suggest that in the Mediterranean context the supposed 4.2 event is formed by two arid phases interrupted by a wetter period, where dryness at ca.4.7 ka is more intense than at ca. 4.2 ka.

Historical River Floods: an integrated approach to identify trends and links with current climate change

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Keywords: historical floods, climate proxies, time series.

Understanding long-term hydroclimatic variability in the Mediterranean region requires high-resolution datasets that extend beyond the instrumental period (Benito et al., 2004) This study reconstructs and analyzes the frequency of flood events in the Arno River Basin (Central Italy) from AD 1167 to 1870 by combining historical documentary sources with advanced analytical methods. A total of 111 flood events were retrieved through a systematic review of local chronicles and archival sources, using and testing an automated process, based on OCR (Optical Character Recognition) and keywords detection, developed to support human search.

The flood time series was constructed at monthly resolution and smoothed using different kernel-based filters over different window lengths. The processed flood series was then compared to several climate and solar proxies, including the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Palmer Drought Severity Index (PDSI) derived from Old World Drought Atlas (OWDA), solar open magnetic flux (OSF), and total solar irradiance (TSI), and Aerosol Optical Depth (AOD), an indicator of atmospheric opacity caused by aerosols produced during volcanic eruptions. All indices were standardized to ensure consistency and comparability with the flood series.

Spearman correlation analysis, conducted across time lags from 0 to 200 years and under multiple normalization schemes, revealed statistically significant (p-value < 0.01) associations between flood frequency and several climate indices, particularly with the NAO, OFS, PDSI and TSI.

The frequency spectrum of the flood event time series was analyzed using Fast Fourier Transform (FFT), and dominant periodicities were tested for statistical significance through Monte Carlo simulations against different types of noises (Brown, Poisson, and white). The results revealed quasi-periodicities in the flood frequency series, from 7 to 180 years.

This integrated approach bridges historical environmental data with modern analytical techniques, offering a robust framework to detect hydroclimatic signals across centuries. The study also highlights the potential of long-term historical series to inform understanding of past flood variability and its links to large-scale climate drivers in the Mediterranean basin.

Benito G. et al. (2004) - Use of Systematic, Palaeoflood and Historical Data for the Improvement of Flood Risk Estimation. Review of Scientific Methods. Natural Hazards, 31, 623-643, https://doi.org/10.1023/B:NHAZ.0000024895.48463.eb.

Human-environment interactions in the Porta Lake protected area during the Late Holocene (Versilia Plain, North Tuscany)

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Keywords: paleoenvironmental reconstruction, human impact, multiproxy analysis.

The Porta Lake natural reserve, established in 1998, is an area of relevant environmental value along the northern Tuscany coastline. It is considered as a remnant of a formerly larger coastal lake in the Versilia Plain, even if different hypotheses and chronologies have been proposed for its formation and evolution (Federici,1998).

The area has been long settled since the Etruscan time and recently recorded the effects of marble extraction from the nearby quarries in the Apuan Alps; however, the role of human pressure on lake environmental dynamics is almost unknown. The Late Holocene scenario has been further complicated by the occurrence of climate oscillations and changes in sediment supply, including floods by the major rivers.

To improve our knowledge on the Porta Lake paleoenvironmental evolution and related forcing factors a scientific coring campaign has been performed in the middle of the lake using a floating platform and a Livingston core equipment.

This allowed the undisturbed recovery of ca. 7 m of lacustrine sediments that have been detailed described in terms of lithofacies and analysed by a multiproxy approach, including grain-size, geochemical, meiofauna and pollens data. Radiocarbon ages indicate a time span covering the last 4 ka BP. An evident environmental change occurred around 1600 CE when an important river diversion occurred according to historical maps and accounts. After the Second World War the lake sedimentation was affected by local marble-related activities, which, once discontinued, allowed the restoration of organic deposits.

Federici P.R. (1998) - L'ex lago di Porta in Versilia (toscana): la storia di una irresistibile pressione ambientale. Memorie Società Geografica Italiana, LV, 397-414.

Analysis of instrumental data for the sustainable management of coastal areas

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Keywords: drainage system, sustainability.

Alluvial-coastal plains and shallow-marine areas are facing increasing hydrological pressure from rising sea levels, changing precipitation patterns, and more frequent extreme events that alter their water balance. Prolonged droughts and unsustainable freshwater withdrawals further exacerbate the problem, causing saline intrusion into already vulnerable aquifers (Hussain et al., 2019). In this context, fine-tuning drainage channel levels has become a key climate adaptation strategy. Our work combines a multi-decadal analysis of hydro-climatic trends (Kow et al., 2024) with near-real-time forecasting to optimize the operation of high-capacity pumping stations (Zhang et al., 2023) that safeguard the drainage network of San Rossore Migliarino Massaciuccoli regional Park (Pisa, Italy). The study approaches two complementary strands of analysis:

1. a multi-decadal analysis of hydro-climatic trends designed to quantify long-term (seasonal) variations in boundary conditions
2. an operational, near real-time forecasting framework designed to support daily management decisions.

In the first case (models with long-term prediction) mainly aquifer level data and meteorological data such as rainfall and temperature will be used. This model will be useful to have a prediction base to refer to in order to determine a certain threshold of pump activation at different times of the year and consequently in different climatic contexts.

In the second case, in addition to meteorological and groundwater data, data on drainage system activity and channel hydrometric levels will be used. In this case, the goal is to create an early warning system for exceptional events where there is limited time to decide when and how to act.

Overall, the preliminary results unequivocally highlight how integrated long-term trend analysis and near-real-time operational forecasting systems are now indispensable for sustainable and resilient water resource management. They make it possible to anticipate critical situations, optimize the use of drainage system, reduce energy consumption and, at the same time, preserve the hydro-saline balance of coastal aquifers. This confirms that fragile alluvial and marine-littoral environments require specific attention, monitoring continuity and technologically advanced solutions to cope with increasingly intense climatic and anthropogenic pressures.

Hussain M.S. et al. (2019) - Management of Seawater Intrusion in Coastal Aquifers: A Review. Water, 11(12), 2467, https://doi.org/10.3390/w11122467.

Kow, P.-Y. et al. (2024) - Watershed groundwater level multistep ahead forecasts by fusing convolutional-based autoencoder and LSTM models. Journal of Environmental Management, 351, 119789, https://doi.org/10.1016/j.jenvman.2023.119789.

Zhang J. et al. (2023) - Data-Driven Parameter Prediction of Water Pumping Station. Water, 15(6), 1128, https://doi.org/10.3390/w15061128.

Climate change and sediment dynamics in Italy: a multi-scale assessment of riverine transport decline and coastal erosion

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Keywords: sediment transport, coastal erosion, climate change impacts.

Sediment transport by rivers is a fundamental process in shaping both fluvial and coastal environments, sustaining floodplain formation, deltaic systems, and coastal stability. Over recent decades, this balance has been significantly altered due to the interplay of climate change, anthropogenic pressures, and critical gaps in systematic sediment monitoring (Besset et al., 2019).

This study presents an integrated assessment of the century-long evolution of sediment dynamics in Italy, combining historical data analysis, satellite remote sensing, and machine learning models. A detailed reconstruction of sediment transport trends in two representative rivers—the Arno and Ombrone (central Italy)—reveals a marked decline in suspended sediment loads from the 1930s to the present. Statistical and AI-based models demonstrate that climate change is the dominant driver of this reduction, primarily through decreasing precipitation, rising temperatures, and shifts in large-scale atmospheric patterns such as the North Atlantic Oscillation. While human interventions (e.g., damming, land use change) contribute locally, climate-related factors exert an impact estimated to be at least 1.5 times stronger (Luppichini et al., 2024).

At the national scale, shoreline evolution was analyzed along 3,624 km of Italian sandy coastlines (1984–2024) using Landsat imagery and the CoastSat algorithm. Results show that 66% of major rivers are currently associated with coastal erosion, rising to 100% when excluding zones with artificial defenses. River deltas emerge as critical hotspots, with over 75% experiencing erosion on at least one bank. Seasonal patterns were identified, with winter generally showing shoreline accretion and summer characterized by erosion—though notable regional exceptions exist (e.g., Liguria, Gulf of Taranto) (Luppichini & Bini, 2025).

This environmental crisis is compounded by fragmented and inconsistent sediment monitoring efforts. Following the dissolution of the national hydrographic service in the 1990s, data collection became regionally managed and uneven. To address this, a centralized PostgreSQL-based database with a web interface has been developed to integrate historical and new sediment data. This platform supports data sharing among researchers, authorities, and land managers, providing a critical tool for future research and planning.

Overall, Italian river deltas represent some of the most vulnerable areas to the combined impacts of climate change and human activity in the Mediterranean. Only integrated approaches—combining environmental monitoring, coordinated data infrastructure, and adaptation planning—can ensure the sustainable management of sediment dynamics and coastal resilience.

Besset M. et al. (2019) - Multi-decadal variations in delta shorelines and their relationship to river sediment supply: An assessment and review. Earth-Science Reviews, 193, 199-219, https://doi.org/10.1016/j.earscirev.2019.04.018.

Luppichini M. & Bini M. (2025) - 40-Year shoreline evolution in Italy: Critical challenges in river delta regions. Estuarine, Coastal and Shelf Science, 315, 109166, https://doi.org/https://doi.org/10.1016/j.ecss.2025.109166.

Luppichini M. et al. (2024) - Climate change as main driver of centennial decline in river sediment transport across the Mediterranean region. Journal of Hydrology, 636, 131266, https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.131266.

Cores: an open-source web platform for the digitalization and integrated management of sediment core

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Keywords: software, core, sediment.

The effective archiving and management of data extracted from sediment cores is a key challenge in geological, paleoenvironmental, and archaeological research. Sediment cores represent natural archives that preserve crucial information for reconstructing past environmental, climatic, and anthropogenic processes. However, the documentation and storage of these cores often occurs in fragmented and inconsistent ways: each research group tends to adopt its own workflow and format, while analytical results from laboratories (e.g., dating, geochemistry, biostratigraphy) are typically heterogeneous in structure, terminology, and file format. This lack of standardization hampers data sharing, comparative analysis, and the integration of sedimentary records across different regions or research programs.

To address these limitations, we present *Cores* (https://lca.dst.unipi.it/Cores/), an open-source web platform designed for the digitalization, structured archiving, and collaborative management of sediment core data. The system enables the digital representation of core stratigraphy, including the definition of lithological units, contact points, sedimentary facies, and chronological sequences. Each interval can be linked to samples with associated laboratory analyses such as radiocarbon or OSL dating, grain size distributions, chemical composition, pollen, foraminifera, meiofauna, and other datasets. All information is stored in a structured PostgreSQL relational database, designed to ensure data integrity, accessibility, and reusability.

Cores also supports the storage and visualization of image data and 3D models obtained through *Structure from Motion* photogrammetry, allowing researchers to archive and interact with high-resolution visual representations of the core surfaces—an often overlooked yet valuable aspect in sedimentological analysis.

The platform is accessible via a web interface built entirely on open-source libraries and frameworks. It offers tools for collaborative editing, permission management, file attachment (e.g., PDFs, images, raw data), and data export in open formats (CSV, JSON). Cores can be used to organize core records into macro-areas or projects, to generate standardized descriptive sheets, and to compare stratigraphic profiles across multiple sites.

By providing a flexible yet standardized digital environment, *Cores* serves as a robust and scalable solution for long-term data preservation and interdisciplinary research, fostering transparency, reproducibility, and interoperability in sediment core studies.

Environmental and human control factors on the Holocene evolution of Venice lagoon: stratigraphic, sedimentological and geochemical approach

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Keywords: Venice lagoon, sedimentology, geochemistry.

Lagoons are among the most fragile ecosystems, naturally susceptible to submersion or infilling over time. Their ecological and socio-economic importance derives from high biodiversity, nutrient availability and their role in global biogeochemical cycles through carbon burial and nitrogen emissions. The evolution of lagoons is primarily driven by climate change, sea level change and human activities, which affect hydrological regimes and sediment dynamics. The variability of these systems is well preserved in sedimentary records, providing valuable insights into past and present environmental conditions. In order to better reconstruct Holocene paleoenvironmental and paleodepositional trends in response to paleoclimatic and sea level fluctuations and anthropogenic influences, 11 sediment cores (4-14 m deep) were drilled at a Roman archaeological site in Lio Piccolo (VE), within the northern Venice Lagoon. These LPC cores were analyzed in terms of facies and then integrated with harmonized additional cores from existing datasets and literature, allowing the construction of stratigraphic-depositional well log correlation panels to improve the understanding of the evolution of this area over the last 25 kyr BP. Three LPC cores were selected for multidisciplinary analysis, the deepest of which has already been dated (Kaniewski et al., 2023). Sedimentology, geochemistry and stable isotope geochemistry were used to characterize facies evolution over the last 8 kyr BP and to refine stratigraphic evidence. The results indicate a transition from a limnic to a paralic environment associated with progressive sea-level rise, with lagoon formation occurring around 6.7 kyr BP, followed by a shift towards coastal conditions between 3 and 2.5 kyr BP, finally leading to the present landscape mainly due to artificial river diversion in the XII-XVII centuries.

Kaniewski D. et al. (2023) - Holocene Sea-level impacts on Venice Lagoon's coastal wetlands. Global and Planetary Change, 236,104426, https://doi.org/10.1016/j.gloplacha.2024.104426.

The paleoenvironmental history of Peloro Cape (Sicily, Italy) reveals landscape transformations and legacies due to human activity since the Bronze Age

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Keywords: coastal environment, olive trees, landscape legacies.

Since the onset of stable human occupation, natural ecosystems and their resources have been increasingly exploited and significantly transformed. This long-lasting process produced enduring legacies in the ecological, morphological, and cultural characteristics of the landscape. Coastal areas have been particularly impacted due to their historical role as key contact zones and critical nodes along trade and transit routes. Southern Italy, in particular, has historically served as a gateway for the exchange of goods and cultural interactions between the eastern and western Mediterranean.

Within the framework of a multidisciplinary collaboration involving paleoecologists, Quaternary geologists, historians and archeologists from various international institutions, we present the high-resolution paleoenvironmental reconstruction of the Peloro Cape area (Eastern Sicily, Italy) spanning the last four millennia. In 2019, a ~730 cm-long sediment core was extracted from the coastal salt marsh of Pantano Grande (a.k.a. Lago di Ganzirri), located along the ancient trade corridor of the Messina Strait. The core was dated using a combination of radiocarbon analysis and geochemical fingerprinting of two volcanic ash (tephra) layers. Results indicate a continuous and relatively stable sedimentation rate from the base of the core (3720 BP) to the sediment-water interface, corresponding to the year of sampling (2019).

A multiproxy analysis – integrating lithostratigraphy, geochemistry, meiofaunal assemblages, and palynology – reveals the extent and dynamics of human-induced environmental change since the beginning of the sedimentary record. Around 3700 years ago, fossil pollen evidence indicates the anthropogenic spread of olive trees (*Olea europaea*), which altered the composition of native vegetation. This phase ended in the 12th cen. BCE (ca. 3200 BP), following the arrival in Sicily of populations from the Italian peninsula and the increase in maritime piracy. A resurgence of human impacts is evident in the 6th cen. BCE (ca. 2600 BP), coinciding with the establishment of Greek colonies. This period is characterized by widespread deforestation and intensified land use, coupled with increased precipitation, which collectively accelerated soil erosion and debris supply. These processes may have contributed to the formation of a barrier separating the marsh from the open sea. During Roman times, the area experienced renewed olive cultivation. However, subsequent sociopolitical changes prompted shifts in land-use practices, including phases of abandonment and rewilding. The complex paleoenvironmental history of the Peloro Cape area testifies how the morphology, ecology and functioning of this area have been shaped—directly or indirectly—by human activity over the last four millennia.

A new 7000-year high-resolution sedimentary pollen record from the ancient Lake Bientina alluvial plain (northern Tuscany, Italy)

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Keywords: palynology, palaeoecology, human pressures.

Understanding the forces that have shaped present-day environments is essential for developing informed strategies to address the challenges posed by future climate and land use changes. Palaeoecological research plays a critical role in this endeavor by providing long-term perspectives on how landscapes have responded to both natural and anthropogenic pressures. This has led to an increasing focus on reconstructing historical human–environment interactions in order to clarify the extent, nature, and legacy of anthropogenic influence across different temporal and spatial scales.

Here we present the high-resolution palynological analysis of a new sediment core collected in 2019 in the Tanali Natural Reserve (Caccialupi, PI). Situated in the former basin of Lake Bientina – which was ultimately reclaimed in the mid-19th century – the site offers valuable insights into long-term ecological change in a remnant wetland-woodland area that escaped modern reclamation and cultivation. The composite sediment core, totaling 11 meters in length, was chronologically constrained using AMS radiocarbon dating on eighteen plant macrofossils, including wood fragments and leaves. The resulting age–depth model spans approximately the last 7,000 years. During the mid-Holocene, the pollen record indicates a gradual decline in mesophilous forest species, such as silver fir (*Abies alba*), reflecting the decline of silver fir populations in the alluvial plains likely driven combined early anthropogenic pressures and climatic changes. Evidence of cereal cultivation emerges during two distinct phases corresponding to the Copper and Bronze Ages, each associated with a noticeable reduction in arboreal pollen, suggesting significant land cover change. Over the past two millennia, chestnut (*Castanea sativa*) became increasingly prominent, particularly during the Medieval period. Riparian taxa, notably alder (*Alnus glutinosa*) and willow (*Salix* spp.) – currently dominant in the Tanali Reserve – began expanding around 2,500 years ago, following the decline of Bronze Age agricultural activity.

Linking deglacial climate forcing to sediment deposition, vegetation shifts, and organic matter preservation in the Adriatic Sea

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Keywords: deglaciation, depositional processes, climate forcing.

The last sea-level lowstand, combined with the extensive Alpine and Apennine glaciers, funneled Italian continental runoff, forming a paleo-river system that drained the Adriatic shelf. Sediments were primarily deposited in the Middle Adriatic Depression, making this basin ideal for studying changes in sedimentation, vegetation dynamics, and organic matter preservation influenced by climatic forcing over the past 16,000 years. A fine-grained sediment core from the distal Po River wedge was investigated using organic carbon stable isotopes, high-resolution XRF core scanning, thin sections, and fossil organic molecules (i.e., biomarkers). This multidisciplinary approach allowed us to track variations in nutrient concentration, sea surface temperature, bottom oxygen conditions, river runoff, and sediment provenance. We propose that climate change across the deglaciation forced environmental changes, such as stepwise sea-level rise and thermohaline circulation, which in turn influenced depositional processes during the final phase of margin progradation and the subsequent abandonment of the system at the shelf edge. Our results show that the last deglaciation records a progressive increase in sea surface temperature, a decrease in terrestrial input, and a change in vegetation likely reflecting differences in temperature and precipitation. Besides, the sediment provenance changed from the Alpine to the Apennine and Hellenic sectors, and the shelf-edge system transitioned from river- to marine-dominated. Superimposed on this trend, high-frequency (millennial-to-centennial) changes in nutrient availability and organic matter preservation occurred especially at the beginning of the Younger Dryas and the Sapropel S1 intervals, that we link to a weakening of the oceanographic circulation and stratification of the water column. Our findings offer a more comprehensive understanding of how depositional processes and carbon burial respond to regional climate forcing.

Acknowledgments: PRIN PNRR 2022 - Prot. P2022LMCW2-SettorePE 10- “CLOSER: CLimate forcing On Adriatic SEa deoxygenation: A multi-archive Reconstruction of Sapropel S1”. CUP B53D23033660001.

Holocene delta dynamics and phases of environmental degradation from the Po Delta record (N Adriatic): the role of climate and human pressure

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Keywords: meiofauna, environmental quality, river inputs.

Several studies have documented the strong impact of fluvial processes on shelf communities, determining changes in both species diversity and composition (e.g., Van Der Zwaan & Jorissen, 1991; Berensmeier et al., 2023). These changes record the benthos response to a complex array of environmental variations brought by river inputs on the seafloor, including highly hydrodynamic levels, in proximity to river mouths, and increasing fluxes of fine-grained materials (organic and inorganic) at more distal areas.

In shallow-marine areas the degree of fluvial influence can frequently vary in time and space, depending on the complex relationship between delta and sea processes that involve river mouth's location, sediment loads and the dominant circulation in the basin, among the most important. These factors are, in turn, potentially influenced by natural (e.g., climate changes and river dynamics) and/or anthropic (e.g., river regulations, dams' construction) forcings.

The multiproxy study of sediment cores retrieved close to the main river branches of the Po Delta (N Adriatic Sea) has allowed the reconstruction of Holocene depositional trends, highlighting phases of environmental degradation linked to delta lobes dynamics. Specifically, the multivariate analysis of meiofauna (benthic foraminifers and ostracods) supported the identification of major shifts in paleocommunities and a detailed facies characterization of the shallow-marine, muddy succession. The availability of a robust stratigraphic and chronological (radiocarbon ages) framework strengthened the recognition of degradation phases by the application of an ecological index, based on species sensitivity to organic-enrichment (AZTI Marine Biotic Index-AMBI; Borja et al., 2000).

The first increasing stress-gradient occurred at the establishment of delta progradation, in response to the deceleration of relative sea-level rise around 7000 yrs BP, and it is tracked by the partial replacement of sensitive species by those tolerant to organic-enriched bottoms (opportunist species). However, the major step towards more eutrophic and then degraded conditions took place much later, during the Roman Age, when extensive human land-use contributed to the development of a fast-prograding, river-dominated Po Delta (Maselli & Trincardi, 2013).

In historical times, the activation/abandonment of delta lobes guided by natural (e.g., Late Middle Age Ficarolo avulsion) or anthropogenic (e.g., Porto Viro diversion-17th century) events have led to additional modifications on the N Adriatic shelf, revealing the importance of an in-depth understanding of the relationships between depositional processes and marine fauna for a robust evaluation of the environmental quality status.

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A multiproxy approach to track Holocene depositional dynamics and environmental stress in the Authie estuary (N France)

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Keywords: benthic foraminifera, remote sensing, ecological quality.

The Authie is a northern France coastal river ~130 km long. Its estuary is a highly dynamic macrotidal system, with tidal ranges reaching up to 10 m (Marion, 2007). Littoral drift, driven by winds, tides, and coastal currents, is well documented since the 12th century and promotes progradation along the southern margin and erosion along the northern margin. These natural processes have been intensified by anthropogenic activities, including the construction of polders and embankments for agricultural purposes (Dobroniak, 1999).

Due to its rich biodiversity and the variety of natural environments — e.g. dunes, salt marshes (schorre), and tidal flats (slikke) — the Authie estuary is a protected area of major scientific and conservation interest.

This study aims to reconstruct recent environmental and depositional dynamics by comparing modern and past conditions, using an interdisciplinary approach based on the integration of sedimentological, geochemical, micropaleontological (benthic foraminifera), and remote sensing analyses.

Modern surface samples were collected along four transects covering tidal flats and low to high marsh zones of the southern margin, while past samples come from a 77 cm-long sediment core drilled in the prograding southern salt marsh and recording the slikke-schorre passage. Radiocarbon, ^{137}Cs and ^{210}Pb dating will provide a robust chronological framework to better constrain this transition and estimate variations in the sedimentation rates, potentially affected by human interventions such as embankments, damming, and river management. Stratigraphic reconstruction will be supported by remote sensing analyses to track shoreline displacement using historical maps (up to ~1000 years old) and aerial imagery from the past century. The NDVI index will be used to discriminate vegetated (schorre) and non-vegetated areas (slikke).

The high sampling rate along the core (1 sample per cm), combined with data from the modern dataset and previous studies from the northern margin, allows us to detect even subtle paleoenvironmental changes in the estuary. Specifically, isotopic data on carbon (C) and nitrogen (N) help trace shifts in organic matter sources —distinguishing between marine and terrestrial sources— and nutrient inputs, while variations in benthic foraminiferal assemblages detect changes in water level and substrate type.

Finally, data integration and comparison will allow us to evaluate recent variations and trends in environmental stress, along with biodiversity changes under the influence of human forcing factors, contributing to better understanding the evolution and vulnerability of the Authie estuarine system.

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Early to Middle Holocene humid period in the central Mediterranean at time of Sapropel S1 formation as revealed by speleothem deposition in the Serratura Cave (Southern Italy)

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Keywords: Middle Holocene, speleothems, Serratura cave.

Sapropel S1 in the Eastern Mediterranean is considered the evidence of sea stagnation related to the increasing freshwater input connected to the southward shift of the African monsoon system due to increasing summer insolation (e.g. De Lange et al., 2008). A variety of evidence suggests that S1 corresponds to a gradual increase in winter Mediterranean precipitation in central Mediterranean, but evidence is sparse and controversial (e.g. Zhornyak et al., 2011). We present a massive phase of speleothem deposition lasting from ca. 8.5 to 7.8 ka BP in the Serratura archeological cave, which marks a hiatus in human frequentation, and indicates a wet phase with no equivalent in the cave during the Holocene.

This period chronologically corresponds to a wetter phase recognized in stable isotopes in speleothems in the Apuan Alps (Zanchetta et al., 2007) and increasing of cave flooding (Zhornyak et al., 2011). This adds evidence for an increase in winter precipitation during the Early-Middle Holocene.

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Climatic instability at the time of the Roman expansion: data from Central Mediterranean

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Keywords: Roman Era, climate, stable isotopes.

The climate during the Roman Age has attracted the attention of many scholars, having done the backdrop of one of the largest and longest-lasting empires of Europe and for its potential to be an important analogue for the present warming. On the basis on historical and anecdotical consideration the Roman Era is popularly identified as characterized by generally "benign" climate (the so-called "Roman Warm Period") and climate has been considered as one of the potential reasons of the rise and successive decline of the western roman empire (e.g. Harper, 2017). However, regional consistent data on Roman climatic evolution are relatively scarce and controversial. In this work, we present evidence of climatic instability during the period of Roman expansion in the Late Monarchic and Republican periods and the first centuries of the Empire using published and new data from speleothems in the Central Mediterranean. The data reveal a complex regional pattern but also indicate evidence of generalized drier period toward the end of the Republican Period (Bini et al., 2020).

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S18.

Atmosphere-ocean models and reconstructions to enhance understanding of the earth system through time

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Enhancing FAIR Underway Observations: ISOBatA's Legacy and the Role of Ship-Based Infrastructure within InSynC

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Keywords: ISOBatA, InSynC, FAIR data, underway data, digital twins, ITINERIS.

In the Polar Regions, the accelerating impacts of climate change demand robust, high-resolution observational data to reconstruct past ocean and ice dynamics and improve future projections. Underway data collected during research vessel voyages to Antarctica offer a valuable resource for refining climate models and supporting long-term projections. To fully realize their potential, it is essential to enhance their acquisition and use by embedding FAIR data principles into workflows, adopting common international protocols, and integrating real-time data sharing and AI-driven analysis. The Italian research icebreaker Laura Bassi (LB) is targeting persistent data gaps and addressing historical limitations, such as the absence of bathymetry in key areas of Italian Antarctic research, which has limited site characterization and seafloor context.

The PNRA-funded ISOBatA project was the first concrete step in addressing this gap, leveraging LB's transit routes to the Southern Ocean to collect high-resolution multibeam, magnetometric, and sub-bottom data in underexplored sectors. Over the past three years, ISOBatA has delivered open-access datasets, also shared within the IBCSO initiative, providing essential context for interpreting existing sediment cores and other legacy data (e.g., bottom water circulation measurements), thereby improving our understanding of past environmental dynamics recorded within geological archives. This effort led to the ongoing development of LB as a Mobile Italian Marine Observatory for the Study of Antarctica—MIMOSA.

LB's integration into the ITINERIS initiative (Home - ITINERIS HUB) has reinforced the vessel's role within Italy's environmental research infrastructure system and aligned it with broader European efforts for integrated Earth observation, promoting synergies among research infrastructures, including POLARIN (POLARIN – Polar Research Infrastructure Network).

Building on ISOBatA and the ITINERIS frameworks, we aim to transform LB into a comprehensive mobile observatory by integrating the acquisition of a wide range of underway data (including atmospheric, oceanographic, biogeochemical, and biological parameters) shared in real time or used for the in-situ calibration of satellite observations. This approach aligns with the goals of the Antarctic InSynC initiative, coordinated by the Alfred Wegener Institute, which fosters coordinated, synchronized, multi-platform observations; standardized FAIR-compliant data acquisition; and the development of digital twins to enhance understanding and prediction of polar environmental processes. Achieving these objectives requires close collaboration between the scientific community and infrastructure operators, including LB and the NADC (National Antarctic Data Center), joint efforts are essential to complete the transformation of Laura Bassi into a mobile observatory and consolidate Italy's contribution to coordinated polar research.

The susceptibility to snow avalanches in the contest of climate change: the case study of Abruzzo region (central Italy)

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Keywords: susceptibility, snow, avalanches.

In mountain landscape, snow avalanches are one of the most dangerous hazards, threatening human life and infrastructures. Because of the high flow speed and pressure, snow avalanches are able to destroy everything along their paths. Moreover, they are one of the mass wasting processes more sensitive to climate change that controls variations in rain–snow partitioning of precipitation and snow cover characteristics (Giacona et al., 2021 and references therein). For these reasons, the assessment of the susceptibility to snow avalanches of mountain regions becomes more and more crucial to mitigate economic and social impacts and to save human lives (Kumar et al., 2019). The occurrence of snow avalanches depends on terrain, meteorological, and snowpack parameters and it can be triggered by an increase of load (caused by human activity or by fresh snow) or by an abrupt warming up (Bühler et al., 2013 and references therein). The terrain parameters are the most easily accessible from analysis of DEMs and from public databases on land use and infrastructures. On the contrary, the meteorological and snowpack parameters are difficult to detect or to be monitored because of their fast evolution in time. For this reason, the terrain analysis provides the base to assess the susceptibility to snow avalanches of a study area. We studied the occurrence of snow avalanches in the Abruzzo Region (central Italy) following two research lines: 1) production of a map of the susceptibility to avalanches; 2) analysis of the variation in temperature and precipitation in the last century for two test locations: Campotosto and Scanno. For the first research line we adapted a method developed for landslides (the so-called ENEA-Roma Tre; Leoni et al., 2014) to produce a map of susceptibility for the mountainous areas of Abruzzo. Starting from the inventory of the snow avalanches during the last 60 years and using slope, elevation, aspect, curvature, and land use as predisposing factors, we obtained a map where the more susceptible areas are characterized by: rocky, grassy, and shrubby steep slopes, exposed to the N-NE and standing at high elevations. This map partially suffers from problems related to the quality of the databases. The second research line is based on the analysis of time-series (from 1918 to 2020) of meteorological data (precipitations and temperature) available for Abruzzo. The results indicate that, although the winter precipitations remained almost constant in the last century, the mean annual temperatures are increasing. Considering the months with higher frequency in snow avalanches, in February both minimum and maximum mean temperatures were found to slightly increase (Scanno) or to be constant (Campotosto), whereas in March they increased by around 1°C in both areas, possibly contributing to the occurrence of snow avalanches.

Bühler Y. et al. (2019) - Automated identification of potential snow avalanche release areas based on digital elevation models. Nat. Hazards Earth Syst. Sci., 13, 1321-1335, https://doi.org/10.5194/nhess-13-1321-2013.

Giacona F. et al. (2021) - Upslope migration of snow avalanches in a warming climate, Proc. Natl. Acad. Sci. U.S.A., 118(44), e2107306118, https://doi.org/10.1073/pnas.2107306118.

Kumar S. (2019) - Geospatial probabilistic modelling for release area mapping of snow avalanches. Cold Regions Science and Technology, 165, 102813.

Leoni G. et al. (2015) - Heuristic Method for Landslide Susceptibility Assessment in the Messina Municipality. In: Lollino, G. et al. (Eds.), Engineering Geology for Society and Territory - Volume 2. Springer, Cham, https://doi.org/10.1007/978-3-319-09057-3_82.

Reconstructing paleo-dynamics of Arctic methane seeps in relation to climate change using geochemical proxies (sediment, foraminifera)

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Keywords: cold seep, Barents Sea, geochemistry.

Seafloor methane emissions are widespread in the Arctic, reflecting the distribution of major geologic reservoirs, gas hydrates, and permafrost. Biogeochemical processes taking place in the sediment drastically reduce the amount of methane eventually reaching the water column and atmosphere, thus representing a critical biofilter for this greenhouse gas. Reconstructing the history of paleo-methane emissions across glacial cycles can help us predict future scenarios by providing analogues of contemporaneous climate change in glaciated margins. Here, we will present case studies from the Barents Sea, describe their present-day biogeochemistry based on sediment and pore fluid geochemical datasets (Argentino et al., 2021; Barrenechea et al., 2025), and explore their dynamics since the Last Glacial Maximum (~19 ka) using geochemical proxies (sediment, foraminifera) for methane oxidation.

Argentino C. et al. (2021) - Dynamic and history of methane seepage in the SW Barents Sea: new insights from Leirdjupet Fault Complex. Scientific reports, 11(1), 4373.

Barrenechea I. et al. (2025) - Sediment eDNA metabarcoding reveals the endemism in benthic foraminifera from Arctic methane cold seepages. ISME Communications, ycaf058.

Global scale impacts of a 21st century AMOC decline

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Keywords: AMOC, climate change, climate modelling.

All models project a weakening of the Atlantic Meridional Overturning Circulation (AMOC) by the end of the 21st century. However, there is large inter-model spread on the amount of the AMOC decline and it is unclear how AMOC impacts overlap with those due to other forcings, primarily increasing concentrations of carbon dioxide. While some studies have shown the global scale impacts of an AMOC shutdown in pre-industrial or paleo conditions, it is not clear how these will play out with the concurrent increase in the concentration of greenhouse gases. In this talk, I will present some novel analysis based on CMIP6 models and idealized model experiments aiming at separating the effects of greenhouse gases from those due to an AMOC decline. Idealized model experiments are carried out with EC-Earth3, a state-of-the-art climate model that participated in CMIP6. We compare control simulations with experiments in which we artificially control the strength of the AMOC by manipulating the virtual salinity flux in regions of deep water formation. Our results show that impacts strongly depend on the background climate, i.e., whether the AMOC decline happens in a pre-industrial state or a greenhouse forced warmer climate. I will show implications for global patterns of temperature, precipitation and large-scale atmospheric circulation patterns. In addition, I will show impacts on daily timescales and implications for extreme temperature events, such as cold spells during winter and heat waves during summer. Finally, I will discuss some outstanding gaps and current research efforts. These include inter-model comparisons that aim to assess the AMOC resilience to freshwater forcing and the possibility of crossing a tipping point in the 21st century.

High-resolution multi-decadal ocean modelling in the Adriatic Sea under a severe climate change scenario: thermal extremes and circulation regimes from the AdriE ensemble

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Keywords: oceanography, climate change, dense water.

Global and regional climate modelling efforts are often not sufficient to capture the small-scale spatial features and the sharp gradients controlling marine processes in coastal systems. As a result, little information is typically given in terms of climate change implications for coastal circulation and the interactions between coast and open sea and between continental shelf and abyssal regions. The Adriatic Sea, located in the northeastern Mediterranean basin, is well representative of processes and pressures that typically affect mid-latitude coastal seas, featuring strongly river-controlled coastal dynamics and a relatively broad continental shelf in which dense water masses are periodically produced, if favourable conditions are met, acting as one of the main gears of the Mediterranean thermohaline circulation and playing a major role in deep sea ventilation.

In order to investigate the possible evolution of these processes and with an eye on the possible implications for adaptation and conservation, a multi-decadal, kilometre-scale Adriatic Ensemble (AdriE) ocean model has recently been developed with reference to a severe (RCP8.5) climate scenario extending to the end of this century. Addressing three-dimensional circulation and thermohaline dynamics within the Regional Ocean Modelling System (ROMS), AdriE consists of 6 climatic runs encompassing the period from 1987 to 2100 in a RCP8.5 scenario forced by the SMHI-RCA4 Regional Climate Model, driven by as many different General Climate Models made available within the EURO-CORDEX Initiative. In the present contribution we explore the AdriE projections focusing on extreme thermal events such as marine heat waves and cold spells, as well as on the possible modifications in circulation regimes, with special emphasis on dense water production. The long temporal extension of the simulations and the inter-model variability entailed in the ensemble approach allow to explore the response of these processes to different meteo-oceanographic drivers as well as to similar drivers under different conditions. Eulerian and Lagrangian methodologies are combined to explore trends and variability in volume and properties of dense shelf water formation over different time scales in the Northern Adriatic Sea, its transport pathways, and the implications for connectivity across the continental margin.

This work lays the foundation for a deeper interdisciplinary assessment of future scenarios in the region and the development of potential management strategies in one of the climate hotspots of the Mediterranean Sea.

Multi-variable assessment of climate changes in the Extended European Alpine Region based on the novel EEAR-CLIM dataset

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Keywords: observations, Alps, climate change.

The European Alps is one of the most vulnerable and sensitive regions to the continuous warming of climate and it is considered an important hotspot of climate change. Climate change assessment in the European Alpine region relies on direct application of climate observations and, thus, their quality may strongly impact climate and hydrological studies results and predictions in terms of reliability, accuracy and precision.

Here, we present an extended analysis of climate changes over the Alpine region during the last decades (1961-2020; 1985-2024). The potential of the recently developed EEAR-Clim observational dataset (Bongiovanni et al., 2025), addressing the key issues in terms of spatial density, data quality, time resolution and completeness, was exploited. The newest version of the dataset, expanded to include relative humidity, wind speed and direction, global radiation, snow depth, snowfall, surface pressure measurements in addition to mean, minimum, maximum air temperature and total precipitation, allows for an even coverage of the extent and the elevation gradient of this area, in terms of most of the essential climate variables. Climate change analysis was carried out on different time scales considering both mean values and a selection of ETCCDI indices. The phenomena of elevation-dependent climate change (EDCC) was also assessed. A pca-based clustering approach was applied to identify climatic regions and evaluate the spatial-dependency of trends. A further analysis concerned the relationship between detrended time series and the main teleconnection patterns. In addition, the time series of the dataset were used to robustly assess the performance of regional and global climate models in reproducing the observed conditions.

Being a study based on the most comprehensive spatial coverage in this area to date, the related results significantly increase the amount of information available to involved stakeholders to prevent and quickly plan for disaster management, risk mitigation and formulating proper locally relevant adaptation strategies.

Bongiovanni G. et al. (2925) - EEAR-Clim: a high-density observational dataset of daily precipitation and air temperature for the Extended European Alpine Region. Earth Syst. Sci. Data, 17, 1367-1391, https://doi.org/10.5194/essd-17-1367-2025.

Tracking climatic changes across the ETM3, ETM2, and PETM events: a preliminary refined age model and magnetostratigraphic study from IODP expeditions

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Keywords: climatic changes, magnetostratigraphy.

This study focuses on reconstructing and characterizing climatic changes associated with the Eocene hyperthermal events ETM3, ETM2, and PETM using a refined age model and magnetostratigraphic framework at IODP Site U1514 (Mentelle Basin). We analyzed 234 sediment samples from depths between 248.2 and 324.68 Top depth (m CSF-A), integrating new laboratory measurements, including alternating field (AF) demagnetization, anisotropy of magnetic susceptibility (AMS), bulk susceptibility, isothermal remanent magnetization (IRM), and anhysteretic remanent magnetization (ARM), with shipboard data reported in the official expedition report. This integrated approach enabled us to develop a high-resolution age model and significantly refine the site's magnetostratigraphy, allowing for precise identification and correlation of the ETM3, ETM2, and PETM intervals. The magnetic property data, in combination with the stratigraphic framework, reveal distinct climatic changes during these hyperthermal events. Our results provide new insights into the timing, magnitude, and paleoenvironmental context of changes during early Paleogene climate perturbations, contributing to a better understanding of the processes and feedback driving extreme climate change in Earth's history.

Atlantification across time: signals from the Arctic gateway

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Keywords: atlantification, foraminifera, biomarker.

Reconstructing climate variability during the Common Era is essential for placing modern human-driven changes into the context of natural patterns, particularly in the Arctic area. This region has experienced significant environmental transformation, closely linked to sea ice decline and the increasing influence of Atlantic waters, a process known as “Atlantification”. In this study, we examine paleoenvironmental conditions over the last few centuries using marine sedimentary sequences collected from the southwestern Barents Sea (cores HH1141, HH1181and HH969) and north of Svalbard (core KH21-234-04), at depths between 174 and 394 m bsl. A multiproxy approach was applied, including excess ^{210}Pb and ^{14}C dating methods, benthic foraminiferal assemblages, geochemical data, and organic biomarkers. The results indicate two main oceanographic intervals. Prior to 1900 CE, benthic foraminiferal assemblages and elevated sea-ice-related biomarkers, reflect cold temperatures and sea-ice cover. In contrast, the 20th century shows a northward, expansion of species associated with warmer Atlantic-derived waters, (*Melonis barleanus, Trifarina angulosa*, *Adercotryma glomeratum)*. Biomarker data further indicates a reduction in seasonal sea ice and increased Atlantic inflow. Together, these results illustrate the onset and intensification of Atlantification over the last century and underscore the value of marine sediment records in tracking oceanographic changes and their broader climatic implications for the Arctic region.

Holocene glacial climate reconstruction: the marine sediment potential in the Western Barents Sea (Arctic Ocean)

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Keywords: Spitsbergen Bank, cold-water carbonate factory, environmental reconstruction.

In recent decades, the urgency of global warming has reignited the drive to unravel past climate dynamics, enhancing our ability to predict future climate changes. Carbonate sediments, particularly those formed by marine biota, represent invaluable climate archives, offering geochemical insights of past climates. The Spitsbergen Bank, in the Western Barents Sea, the world's northernmost cold-water carbonate factory, provides a unique setting to study oceanographic, biological and sedimentological interactions in the Arctic polar realm. In fact, despite extreme seasonality and harsh environmental conditions, an Arctic carbonate factory has persisted on the bank for the past 12,000 years following the ice recession.

During ship opportunity activities within the last HN24 Cruise aboard the R/V Alliance, with the aim to trace Holocene climatic evolution in the arctic region, we collected two cores on the continental escarpment (at 369 and 456 m depth) NW and SW of Bear Island.

Granulometric analyses reveal that mud consistently represents the dominant fraction in these sediments, spanning from 42.91% to 85.97%, while the sand and gravel fraction varies between 14.03% and 57.09%. Calcimetry results indicate that the carbonate content consistently remains below 10%. Micropaleontological analyses showed a diverse fauna constituted mostly by benthic foraminifers, agglutinated as hyaline tests, and subordinated siliceous sponge spicules, ostracods, bryozoans, molluscs and rare echinoid fragments.

Such a high mud content will allow Xray diffraction analysis on clay minerals to identify the provenance of the terrigenous input and its changes through time. The latter, in fact, are potentially linked to changes in the ice cover, alternation of relatively humid and arid phases and different current circulation patterns.

Laslty, retrieving a diverse fauna at such high latitudes marks a preliminary, but not obvious, fundamental step for reconstructing the seawater temperature trends during Holocene. Calcitic benthic foraminifera, in fact, represent an excellent matrix for applying stable isotope geochemistry and trace paleotemperature trends, as well as nutrient dynamics, in seawater, potentially filling an important gap in the paleoclimate reconstructions of marine environments at high northern latitudes.

Large scale circulation patterns associated with different flavours of Arctic Amplification

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Keywords: arctic amplification, circulation, CMIP6 models.

Arctic Amplification (AA), a phenomenon characterised by a faster warming of the Arctic region compared to the global average, emerged in the 1980s as a particularly alarming consequence of climate change.

This thesis investigates how current CMIP6 climate models represent AA by comparing ensemble means with reanalysis data from ERA5.

The thesis aims to better understand which dynamic processes control the characteristics of AA by using the different representations of AA provided by CMIP6 models, in order to identify any possible connection between AA and atmospheric circulation in the Northern Hemisphere.

The study focuses on key atmospheric variables over the Northern Hemisphere for the period 1980-2014, particularly during the winter months (DJF).

Under the same radiative forcing, model outputs and reanalysis data show differences in the representation of AA in association with different dynamic structures.

After establishing which climate model is closer to observational data, our results suggest that the representation of certain feedback mechanisms, especially those related to ice melt, is critical in climate models' ability to accurately simulate AA. Therefore, this research provides valuable insights into the limitations and uncertainties of current climate models and offers a foundation for enhancing the accuracy of future climate change projections.

Global versus regional perspectives on the evolution of monsoon behaviour during the past 6000 years

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Keywords: paleoclimate modelling, Holocene, monsoons.

Monsoons are key component of the global hydrological cycle, as they account for ca 30% of the total global precipitation. Recent trends pointing towards intensification of monsoon due to increased CO_2 are predicted to continue into the future with high confidence. Projections also show expansion of the monsoon domain and an increase in extreme precipitation. Monsoons – circulation associated with large-scale seasonal changes in atmospheric circulation and precipitation driven primarily by changes in isolation and the seasonal migration of the ITCZ, as well as being influenced by local differences in land-sea temperature. During the Holocene, changes in orbital configuration, greenhouse gas concentrations, and land surface feedback have modulated monsoon intensity and spatial extent, yet the relative roles of changes in mean climate state versus variability remain incompletely understood. This gap in understanding limits our ability to robustly attribute past monsoon behavior and to anticipate future changes under anthropogenic forcing. Recent advances in proxy-based reconstructions and the emergence of long transient simulations, unkike mid-Holocene and pre-Industrial equilibrium simulations traditionally used in Paleoclimate Modelling Intercomparison Project studies, provide an opportunity to examine the path between mid-to-late Holocene, a period marked by a transition from a generally wetter and more stable climate to one characterized by greater regional disparities and increased variability. The pronounced long-term weakening of monsoon systems since the mid-Holocene is frequently interpreted through the lens of declining Northern Hemisphere summer insolation, but the underlying mechanisms—particularly the interplay between mean state shifts and variability—remain elusive. In this study, we assess the evolution of monsoon precipitation patterns over the last 6000 years by explicitly disentangling the contributions of mean state and variability to observed changes. We focus on the transition between the mid-Holocene and preindustrial periods, a critical interval that encapsulates the most significant reorganization of monsoon systems in the Holocene. Through an energetic framework, we explore deviations from the global monsoon behavior, identifying key thermodynamic and dynamic mechanisms that shaped regional hydroclimates. Our analysis reveals that the apparent shrinking and weakening of Northern Hemisphere monsoonal intensity is not uniform across regions and cannot be fully attributed to mean state changes alone**.** Instead, we show that spatial heterogeneity and changes in the amplitude and timing of precipitation variability—particularly in response to orbital-scale seasonality—played a central role in modulating "monsoonality," defined here as the combined intensity, spatial coherence, and seasonality of monsoon-driven precipitation. By comparing metrics such as precipitation minus evaporation and shifts in dynamic and thermodynamic drivers, we quantify the evolving contributions of both mean state and variability**.** This framework allows us to characterize the seasonally asymmetric responses of monsoon systems, especially under declining orbital forcing, and to pinpoint the mechanisms behind the transition from a mid-Holocene monsoon maximum to the more fragmented and variable preindustrial state. Understanding these past transitions is not merely of academic interest; it holds important implications for future climate trajectories. As variability patterns evolve under continued anthropogenic forcing, our results suggest that regional precipitation responses may diverge significantly from mean state expectations, with potentially profound consequences for water resources, agriculture, and ecosystem resilience in monsoon-affected regions.

Cook and Ninnis glaciers (East Antarctica) and Ocean interaction in the Pleistocene from marine geological records

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Keywords: Antarctica, ice sheet, contourites.

The glaciers draining the ice sheet covering the subglacial Wilkes subglacial Basin (East Antarctica) and terminating in the Cook Ice Shelf and Ninnis Glacier Ice Shelf contain a volume of ice equivalent to a global sea level rise of 3 to 4 metres. Long-term climate projections and multiproxy studies from ice core records indicate that the intrusion of warm ocean water could trigger the retreat of the ice sheet in this area.

During 2022, the PNRA/COLLAPSE (Cook glacier-Ocean system, sea LeveL and Antarctic Past Stability) project mapped the continental margin in the offshore area at the mouth of the Cook and Ninnis glacier valleys. This talk will present some of the results of extensive work carried out by a large Italian and international team using data collected during the cruise. The combination of geomorphologic, seismic, oceanographic, and sedimentary data allowed the identification of a variety of processes occurring on the seafloor today and in the late Quaternary. Diatom and foraminifera analyses were carried out in conjunction with the sedimentary, geochemical, and petrographic facies analyses on gravity coring transects. The geophysical data show evidence of slope instability before the putative large glacial Cook depression. Sediment drifts controlled by bottom currents grow on channel-levees and slope terraces. This information helps, albeit indirectly, to reconstruct the dynamics of the different glaciers in relation to palaeoclimatic changes and ocean circulation, to estimate their respective contribution to global sea level rise, and to constrain models for future scenarios.

Modeling Paleocene - Eocene hyperthermals with the PlaSim – LSG earth system model of intermediate complexity

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Keywords: paleoclimate, climate change, ESMIC.

Hyperthermal events, such as the Paleocene-Eocene Thermal Maximum (PETM, 56 million years ago) and Early Eocene Climatic Optimum (EECO, 52 million years ago), offer critical insights into how Earth's climate system responds to rapid increases in greenhouse gas concentrations. These episodes of intense global warming and ocean acidification provide valuable analogs for understanding the long-term impacts of abrupt carbon release, with implications for assessing present-day anthropogenic climate change.

In this study, we use a version of the Planet Simulator (PlaSim) (Fraedrich et al., 2005), an Earth Model of Intermediate Complexity (EMIC) improved with a 3D ocean model (Large-Scale Geostrophic ocean model, LSG), to simulate climate conditions during these hyperthermal periods. Simulations are conducted using both a mixed-layer ocean configuration and a full-depth dynamic ocean to assess differences in heat transport, climate sensitivity, and ocean-atmosphere feedbacks. Boundary conditions are based on (Herold et al., 2014) and follow an experimental design similar to the DeepMIP protocol (Lunt et al., 2021), with atmospheric CO_2 levels ranging from 1× to 16× pre-industrial concentrations.

The simulations are analyzed in comparison with both late Paleocene–early Eocene and present-day climate conditions. Emphasis is placed on equilibrium climate sensitivity (ECS), polar amplification, and Antarctic surface warming, shedding light on the mechanisms that may have supported ice-free conditions during the early Eocene. In addition to temperature responses, the study includes detailed analysis of seasonal climatology and a range of atmospheric and surface variables—including cloud cover, mean sea level pressure, sea ice fraction, and snow cover—offering a more complete picture of climate system behavior under extreme greenhouse gas forcing.

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Reconstructing debris flow activity using temperature as a proxy for extreme rainfall conditions

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Keywords: debris flows, extreme rainfall, reconstruction.

Debris flow activity shows nonlinear responses to climate conditions. As debris flows are initiated by torrential rainfall, it is natural to associate debris flow activity to the frequency of sufficiently heavy short-duration rainfall downpours. The Plansee lake (Tyrol, Austria) in the Northern Calcareous Alps showed a nine-fold increase in debris flow activity since 1920 (Kiefer et al., 2021). Such an increase still needs to be fully understood, but it is easy to associate it to the ongoing intensification of extreme short-duration rainfall downpours in the Alps (Dallan et al., 2022). Rainfall observations with sufficient temporal resolution are however available only for relatively short periods – in the Alps they date back 40 years at most. Here, we overcome this limitation using a recent statistical model that uses wet-day temperatures as a covariate to predict the probability of extreme short-duration rainfall downpours (Marra et al., 2024). We combine the statistical model with long-term temperature reconstructions from climate model reanalysis since 1850 using running windows of 2-10 years, and we assess whether the fluctuations in occurrence probability of extreme rainfall downpours predicted by the statistical model based on the reproduced temperature fluctuations is able to reproduce the fluctuations in debris flow activity in the Plansee. In this sense, the Plansee represents an ideal testbed, as it collects sediments from 54 active debris flow channels and therefore samples extreme events that occurred over a relatively large area, as opposed to point observations from individual debris flow basins or direct rain gauge observations.

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Small-sized benthic foraminifera as proxy of the Late Quaternary palaeoceanographic and sea-ice variations in the Kveithola Trough Mouth Fan (NW Barents Sea)

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Keywords: microfossils, paleobiological proxies, sediment cores.

The north-western continental margin of the Barents Sea represents an important gateway for the entry of the relative warm and saline Atlantic Water (AW) into the Arctic Ocean. The influx of AW into the Arctic Ocean fluctuated significantly during the late Quaternary playing an important role on the climatic conditions of the Arctic and forcing the polar front shifting. The western Barents Sea is a crucial region for examining the palaeoceanographic conditions which occurred during the past. Contour currents over the south-western continental margin of the Svalbard area, have produced expanded sedimentary sequences suitable for high-resolution paleoceanographic and paleoenvironmental reconstructions (i.e. Carbonara et al., 2016, Torricella et al., 2025).

We present a high-resolution (centennial scale) from the Storfjorden-Kveithola depositional system (NW Barents Sea) during the CORIBAR projects (Hanebuth et al., 2013). The objective is to reconstruct the paleoceanographic and paleoenvironmental evolution after the Last Glacial Maximum, by means of the planktic and benthic foraminiferal assemblages (fraction > 150 μm) focusing on the small-sized benthic foraminiferal assemblages (fraction 63 - 150 μm).

The chronological framework defined by Caricchi et al. (2018) indicate that the core records the last 14.5 ka BP. The glaciomarine sediments preceding the Holocene contain a low diversified benthic assemblage with *Cassidulina reniforme*, *C. neoteretis*, *Islandiella helenae/norcrossi* and *Cibicides lobatulus*, as dominant species. The benthic foraminifera become abundant in the Holocene sequence as is typically seen for other planktonic microfossils (Carbonara et al., 2016). In particular, the significance of small-sized species (> 63 μm) increased during the Holocene. The beginning of the Holocene is marked by the occurrence of the diatom *Coscinodiscus* spp., a more diversified assemblage of planktonic foraminifera, and the occurrence of *Cibicidoides wellerstorfi*. They support the onset of a warm environmental period related to the Holocene Thermal Maximum (HTM), along with the notable abundance of the small-sized species *Seabrookia earlandi* and *Stetsonia horvathi*. The diversity of the assemblage diminishes at approximately 9.3 ka BP, reaching the minimum values at the 8.2 ka BP cold event, which is characterised by the presence of primary productivity indicators as *Turborotalita quinqueloba*. During the late Holocene, the increasing occurrence of *Epistominella arctica*, *E. exigua*, and *Eilohedra nipponica*, which are phytodetritus feeders, mostly indicates seasonal sea ice conditions.

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Present climate change as a key to understand historical events: the decline of settlements along the Iranian coast of the Persian Gulf (6th-10th centuries)

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Keywords: climate change, Persian Gulf, water stress.

The prosperity of the settlements along the Iranian coast in the 6th and 10th centuries indicates a migration from the northwest to the southeast (Whitcomb, 2016; Callieri et al., 2021; Sembroni et al., 2024). The shifting in the primacy of these ports has been linked to economic patterns, although the topic remains debated (Whitcomb, 2016; Callieri et al., 2021). To contribute to the discussion, we propose the potential impact of climate as a contributing factor. To understand the past, we began by studying the present climate using freely available databases (NASA, CHIRPS, CCKP). Between 1901 and 2020, southern Iran experienced little change in average monthly rainfall, while temperature increased. Relative sea level along the Iranian coast has been rising (1993-2024), whereas groundwater levels have been declining (2002-2024). To refine this general picture, we focused on five coastal location (Bushehr, Dayyer, Lamerd, Bandar Lengeh, and Bandar Abbas) and one inland (Firuzabad). The analysis of precipitations (1981-2024) and their anomalies relative to a long-term average show that: 1) rainfall has become increasingly variable over time, with a slight overall increase; 2) positive anomalies are less frequent but more intense, while negative anomalies (droughts) are more frequent but less severe. Droughts are less pronounced along the southern coast, where the summer months are not completely dry due to the influence of the Indian Ocean Monsoon. Combining these findings with the observed increase in flood frequence (2013-2023), we infer that the total amount of rainfall has not changed significantly, its distribution has. Rain is now concentrated into fewer days, alternating with more frequent droughts. This pattern results in heavy rainfall events that saturate the soil, increasing run-off and limiting groundwater recharge. Recharge is further hindered by rising temperature, which boosts evaporation rates. This limited replenishment affects not only the quantity but also the quality of water, as it becomes more saline due to the salt and gypsum-rich bedrock (Maghrebi et al., 2021). The combination of rising sea levels and declining aquifer levels promotes sea water intrusion, further deteriorating groundwater quality. In short, current climate change is reducing water availability for both agriculture and domestic uses. This is compounded by overexploitation caused by population growth and agriculture expansion (Maghrebi et al., 2021). Based on the results, we suggest that in an arid region -where even minor changes in rainfall and temperature can lead to water stress - the rise of coastal settlements may have increased groundwater extraction, rendering water quantity and quality unsuitable for sustaining communities. Thus, between the 6th and 10th centuries, the northwestern ports gradually declined, while new ones emerged in the southeast, where the Indian Ocean Monsoon ensures greater water availability.

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Supporting Antarctic geoscience: the national Antarctic museum - Trieste section as a repository of marine geological material for the national and international research community

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Keywords: National Antarctic Museum.

Since Italy ratified the Antarctic Treaty in 1981, it has played an active role in polar research through the National Antarctic Research Program (PNRA), established in 1985. This program has enabled numerous Italian research groups to conduct multidisciplinary studies in Antarctica, culminating in the foundation of the National Antarctic Museum (*www.mna.it*). The museum, established by the Universities of Genoa, Siena, and Trieste, is dedicated to the conservation, study, and dissemination of scientific knowledge derived from Italian Antarctic expeditions. It houses a wide range of samples—including biological, mineralogical, lithological, glaciological, and marine geological materials—and promotes public understanding of polar science. Each of its three sections comprises a permanent exhibition, a study and sorting centre, and a documentation centre.

The Trieste Section of the National Antarctic Museum functions as the primary repository for marine geological material collected during PNRA expeditions. Its holdings include over 1,000 meters of deep-sea sediment cores, approximately 1,400 kilograms of dredged and grab samples, and 50 meters of box cores from both Antarctic and sub-Antarctic (Magellan) regions, as well as coastal and lacustrine samples. Samples are preserved under controlled conditions: archival materials are stored at 4°C, selected samples are frozen, and subsamples intended for sedimentological analysis are kept at room temperature. This infrastructure plays a key role in ensuring the long-term conservation and accessibility of marine geological materials, thereby supporting both current and future scientific investigations.

A dedicated GIS database accompanies the collection, providing metadata such as expedition identifiers, core labels, geographic coordinates, and water depths. It also includes digitized X-ray images and preliminary core descriptions, offering a rich and navigable resource for researchers worldwide. By enabling sample access upon request and encouraging collaborative research, the Trieste Sorting Centre actively contributes to international scientific engagement and the advancement of Antarctic geoscience.

Sea ice fluctuations in the Baffin Bay and the Labrador Sea during periods of glacial abrupt climate changes

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Keywords: abrupt climate changes, ice core, sediment core.

Sea ice decline in the North Atlantic and Nordic Seas has been proposed to contribute to the repeated abrupt atmospheric warmings recorded in Greenland ice cores during the last glacial period, known as Dansgaard-Oeschger (D-O) events. However, the understanding of how sea ice changes were coupled with abrupt climate changes during D-O events has remained incomplete due to a lack of suitable high-resolution sea ice proxy records from northwestern North Atlantic regions. Here, we present a subdecadal-scale bromine enrichment (Brenr) record from the NEEM ice core (Northwest Greenland) and sediment core biomarker records to reconstruct the variability of seasonal sea ice in the Baffin Bay and Labrador Sea over a suite of D-O events between 34 and 42 ka. Our results reveal repeated shifts between stable, multiyear sea ice (MYSI) conditions during cold stadials and unstable, seasonal sea ice conditions during warmer interstadials. The shift from stadial to interstadial sea ice conditions occurred rapidly and synchronously with the atmospheric warming over Greenland, while the amplitude of high-frequency sea ice fluctuations increased through interstadials. Our findings suggest that the rapid replacement of widespread MYSI with seasonal sea ice amplified the abrupt climate warming over the course of D-O events and highlight the role of feedbacks associated with late-interstadial seasonal sea ice expansion in driving the North Atlantic ocean–climate system back to stadial conditions.

On the role of AMOC weakening in shaping wintertime Euro-Atlantic atmospheric circulation

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Keywords: climate change, AMOC, weather regimes.

Climate change simulations project the slowdown of the Atlantic Meridional Overturning Circulation (AMOC) in the 21st century, a key component of the global climate system. In the Euro-Atlantic region, where the AMOC strongly influences sea surface temperature (SST) variability, climate projections also show significant uncertainty in the evolution of large-scale atmospheric circulation. We hypothesise that the decline of the AMOC and the uncertainty in Euro-Atlantic atmospheric circulation are interconnected. To test this, we analyse three coordinated climate experiments from the CMIP6 archive (SSP2-4.5, SSP5-8.5 and abrupt-4xCO_2) adopting a storyline approach. In particular, we compare groups of models projecting a larger AMOC decline to groups of models projecting a smaller AMOC decline. Our results indicate that a stronger AMOC weakening is associated with an intensification of the North Atlantic storm track and jet stream, as well as an increased frequency of the NAO+ weather regime. We link these atmospheric changes to the influence of a reduced warming of the subpolar North Atlantic, known as the North Atlantic Warming Hole (NAWH), associated with the AMOC weakening. To further support our findings, we conduct an additional experiment using the EC-Earth3 model, comparing an abrupt-4xCO_2 experiment with one where the AMOC is fixed at preindustrial levels. This experiment corroborates the CMIP6 analysis and validate our hypothesis. We conclude that the AMOC plays a critical role in driving atmospheric changes over the Euro-Atlantic region. Improved monitoring and better constraints on future AMOC decline would help reduce uncertainty in predictions of atmospheric circulation and climate impacts over Europe.

The response of the East Antarctic Ice Sheet to climate changes: insights from petrographic and mineralogical investigations in George V Land coast

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Keywords: Antarctica, provenance study.

The PNRA-COLLAPS (Cook glacier-Ocean system, sea LeveL and Antarctic Past Stability) is a multidisciplinary project that aims to investigate ice-ocean interactions in a sector of the East Antarctic Ice Sheet that is deeply sensitive to global warming. The Wilkes Subglacial Basin, which drains through the Cook, Ninnis, and Mertz glaciers along George V Land, hosts an ice volume equivalent to a potential global sea level rise of 3-4 m.

The project combines geomorphologic, seismic, oceanographic, and sedimentary data to identify the variety of processes occurred on the seafloor from the Late Quaternary to present day.

Sediment cores collected in front of Cook and Ninnis glaciers provide a unique geological record to understand the response of this sector of the East Antarctic Ice Sheet to climate variability that characterize the late Quaternary.

Provenance study of sediments allows to identify changes in the source regions over time, reflecting variations in ice volume and paleoenvironmental conditions.

Here we combine high-resolution analyses on a wide grain-size spectrum, from silt up to gravel. The heavy minerals have been separated from silt and fine sand fractions and then identified with microscope and Raman spectroscopy. Coarse sand and gravel have been investigated with petrographic techniques coupled with mineral chemistry. The clast lithology and heavy minerals assemblages vary between glacial and interglacial settings, supporting a provenance from the George V Land coast in glacial intervals, while distal sources related with floating icebergs are hypothesized during interglacials.

S19.

Microfossils and geochemical proxies: fundamental tools for the reconstruction of Earth history

CONVENERS AND CHAIRPERSONS

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Refining Lower Pliocene paleoenvironmental reconstructions through integrated microfaunal analysis: Insights from Vallone Tora (Southern Apennines)

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Keywords: paleoecology, biostratigraphy.

This study presents new paleoenvironmental data about the Vallone Tora section, a Lower Pliocene neritic succession deposited in the wedge-top setting of the Ariano Basin (Southern Apennines). In this sector of the basin, upper Zanclean north-eastward alluvial progradational system (Ciarcia et al., 2006) and a gradual transition, from neritic to low-gradient nearshore facies, occur. Biostratigraphical analysis of these deposits highlights the presence of *Globorotalia puncticulata*, allowing it to be referred to the upper Zanclean (biozone MPl4a, MNN14–15/MNN16a partim, CN11b–CN12a partim; Ciarcia & Vitale, 2013). Through the combined analysis of benthic foraminiferal and ostracod assemblages, retrieved from 15 samples collected in the pelitic levels, we show how the interplay between these two microfossil groups enhances the paleoecological characterization of the depositional environment. The joint interpretation of taxonomical, ecological and statistical analyses shows a complex scenario: where benthic foraminifers indicate a prevailing low-oxygen regime, the ostracods provide key paleobathymetric constraints that align with – and improve – the foraminiferal data, indicating a transgressive trend in a neritic platform environment; however, anomalies in the composition of the benthic foraminifer assemblages in the lower part of the succession, raise the possibility of allochthonous inputs, emphasizing the need of a multi-proxy perspective. The application of the Revised Benthic Foraminiferal Oxygen Index (R-BFOI), based on the considerations of Kranner et al. (2022), further refines the interpretation of Dissolved-Oxygen (DO, ml/l) levels compared to the traditional BFOI firstly proposed by Kaiho (1994), further detailing the paleo-oxygenation conditions across the succession. Two paleoenvironmental models are proposed: a progressive deepening of an autochthonous shelf environment, and an alternative that considers allochthonous influences in the lower samples. These findings offer refined paleoecological constraints for the interpretation of the Pliocene depositional settings in the Ariano Basin.

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To be or not to be, the question of reproductions in Lower Jurassic Dasycladales, the case of *Palaeodasycladus elongatulus* (Praturlon) from Italy

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Keywords: Dasycladales, *Palaeodasycladus elongatulus*, Central Apennines.

The Latium-Abruzzi Domain is one of the paleogeographic domains in the Central Apennines includes the Lower Jurassic "Calcari a Palaeodasycladus" Formation, which is characterized by shallow-water carbonates, biomicritical limestones and by the presence of oncoids, dasycladeans algae, ooids and fragments of gastropods or bivalvs. *Palaeodasycladus* is a typical genus of dasycladaleans algae that are found in Triassic-Jurassic sediments of the Central Apennines.

The taxonomic history of the species related to *Palaeodasycladus* has been controversial. Diagnostic characters such as the shape of tallus, shape and dimensions of primary laterals, number of laterals, kind and position of reproductive organs are a matter of debate. In the past, several authors proposed different attributions. Still, the main controversy is related to the attribution of *Palaeodasycladus elongatulus* as a variety of *Palaeodasycladus mediterraneus.* Principal similarities between *P. elongatulus* and *P. mediterraneus* are the basic morphology and the arrangement and mode of ramification of the branches. The main differences stand in the shape of the thallus, which is thinner and slenderer in *P. elongatulus*, and the shape of laterals, which in *P. elongatulus* are very thin and long.

Here we analyze *P. elongatulus* specimens occurring in samples taken in two different localities from Abruzzi Region: Monte Palombo, type locality of the species, near Pescasseroli and Corno Grande in the Gran Sasso massif.

The genus *Palaeodasycladus* is characterized by a club-shaped thallus made by a wide rounded head attached to an almost cylindrical narrow stem. Primary laterals, when preserved, are rather inclined. Secondary and tertiary laterals would follow the primary ones. In the swollen upper portion of the thallus only tertiary laterals and part of the secondary ones are apparent. No trace of reproductive organs is detected. Therefore, we suppose cladosporous reproduction. The main difference between *Palaeodasycladus* and the coaeval *Eodasycladus* Cros and Lemoine, is the occurrence of one external gametophore set terminally to the primary lateral of this latter genus.

In keeping with the emended diagnosis, we suggest that several species formerly ascribed to *Palaeodasycladus* should be safely moved to *Eodasycladus* (Barattolo et al., 1994, 2012). *P. elongatulus* from type locality displays characters fitting well with the description given by Praturlon (1966) and the characters of the genus *Palaeodasycladus*. The specimens from the Gran Sasso are strictly comparable with those from type locality but clearly display terminal gametangia like in the genus *Eodasycladus*. Therefore, in the face of a morphological identity at species level the two populations studied should paradoxically belong to two different genera. A hypothesis to explain such a puzzling condition is prospected. Additional Lower Jurassic genera are here discussed for the presence of external gametangia.

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Benthic foraminifera as bioindicators for the environmental characterization of the Tyrrhenian shelf (Central Italy). Preliminary results from the Civitavecchia area

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Keywords: benthic foraminifera, marine sediments, environmental indicators.

In the last two decades, the application of benthic foraminifera (BF) in the field of environmental research has greatly developed, mostly based on the experience of using the fossil ones for the reconstruction of paleoenvironments. These single-celled organisms are generally very abundant, highly diversified, and have a short life cycle; for these characteristics, they are reliable and sensitive descriptors of the environment they live in, providing indicators based on statistically significant quantitative data to be used as proxies of natural and anthropogenic environmental changes. Nevertheless, there is still an incomplete understanding of the foraminiferal response to environmental variability in different marine habitats.

To improve this knowledge, a survey has been carried out during 2024 in 3 sectors of the Tyrrhenian shelf with different textural and morphological characteristics, to highlight the response of recent BF to variability of seabed morpho-bathymetry, sediment texture and degree of anthropogenic pressure. Among these, the marine coastal sector in front of Civitavecchia town was chosen because affected by high anthropogenic impact due to the presence of an important harbour, a coal power plant, and a populated urban centre. A total of 66 sediment samples were collected using a box-corer along transects perpendicular to the coast, down to 126 m water depth, for the study of grain size and of living and dead BF. The collected sediments have been sub-sampled in 2 cm levels, down to 12 cm.

The preliminary results of BF from more coastal stations highlighted assemblages dominated by epifaunal-epiphytic taxa, such as *Asterigerinata planorbis* and *Gavelinopsis praegeri*, close to the lower limit of *Posidonia oceanica* meadows. Nevertheless, highly opportunistic species, such as *Nonionella turgida* and *Valvulineria bradyana* prevailed in some samples, pointing to an environmental stress of possible anthropogenic origin.

The results of this study contribute to the knowledge for the implementation of BF in environmental biomonitoring. Identifying new reliable descriptors of the marine ecological status may be an opportunity to improve the environmental legislation. This approach, deriving from micropaleontological methods, testifies to how the geosciences contribute to new, promising application areas.

Calcareous Nannofossil variability controlled by Milankovitch and sub-Milankovitch periodicity in the Monte San Nicola section (Gelasian GSSP)

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Keywords: Gelasian, Pliocene/Pleistocene boundary, nutricline depth variation.

In Monte San Nicola section, the top of A5 sapropel ("Nicola bed") is the Global Boundary Stratotype Section and Point (GSSP) of the Gelasian Stage, between Pliocene and Pleistocene Series and Neogene and Quaternary Systems. It is a boundary of great interest in Stratigraphy because it corresponds to an interval of global paleoclimate evolution that marks the switch from "Cool-house" to "Icehouse" climate states, a key event in the climatic evolution of the Cenozoic. This interest is expressed by the recent effort of different research groups, that are revisiting the GSSP with modern analysis techniques and approaches (Capraro et al., 2022; Radmacher et al., 2023; Addante et al., 2024; Zanola et al., 2024). This study deals with the new data on the calcareous nannofossil assemblages observed in the sediments from Monte San Nicola area. It is aimed to assess and delineate the paleoenvironmental changes in the photic zone during the Pliocene-Pleistocene transition. In this way we intend to improve knowledge of the underlying mechanisms and regional responses to the intensification of the Northern Hemisphere Glaciation, which initiated from the glacial Marine Isotopic Stage (MIS) 100 and culminated with the definitive establishment of large Northern Hemisphere Ice Sheets and the periodic deposition of ice-rafted detritus (IRD) in the North Atlantic. Calcareous nannoplankton/nannofossils are employed both in biostratigraphic and paleoenvironmental/paleoclimatic studies. They quickly respond to orbital and suborbital climate changes, at least since the Middle Pleistocene, especially in the Mediterranean area where these phenomena are significantly amplified. Calcareous nannoplankton also provide useful information for paleoenvironmental changes during the deposition of sapropel layers that represent a paleoceanographic extreme in terms of water mass physical-chemical properties and thermohaline circulation. Here we show high temporally resolved calcareous nannofossil data from the Monte San Nicola 'Mandorlo' section. We planned the study of this section to complement a similar investigation on the historical type-section in which the Gelasian GSSP was defined, that gave poor results. From our preliminary analysis the nannofossil assemblages in the type-section appeared strongly affected by reworking of Neogene taxa, mostly *Discoaster* species, which obscured the biostratigraphic signal and hampered reliable palaeoenvironmental reconstructions. Furthermore, faulting and poor exposure conditions, observed a few meters above the Piacenzian/Gelasian boundary, compromised the type-section suggesting that the local stratigraphy was not continuous. By contrast, distribution patterns of taxa and groups in the 'Mandorlo' section and their statistical and signal analysis provide a sound new proof of concept for the reconstruction of the sea surface environment and water column dynamics across the Gelasian GSSP.

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The first calcareous nannofossil-based paleoclimatic reconstruction of the last 27,400 years in the Ligurian Sea (Italy)

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Keywords: paleoclimate, Northwestern Mediterranean, last glacial-interglacial.

The climatic events that marked the last 28 ky (e.g., Heinrich Stadials - HS, Last Glacial Maximum - LGM, Younger Dryas - YD, Bølling-Allerød - BA) have been recorded in the Mediterranean Sea. However, areas like the Northern Tyrrhenian Sea remain poorly investigated. The analysis of calcareous nannofossil assemblages from gravity core NDT_22 provides new insights into the paleoceanographic and climatic evolution of the Ligurian Sea over the past 27.4 ka. The 320 cm-long core, collected at 436 m depth during the NEXTDATA2016 cruise aboard R/V Urania (CNR), consists of greenish to greyish fine sediments that were sampled every 2 cm. Nannofossil distribution was examined using nannofossil accumulation rate (NAR) (Flores & Sierro, 1997) and relative abundance (%). Cluster analysis was used to identify key climatic phases. The distribution of Warm Water (WWG), the Cold Water (CWG) and placolith groups was investigated along with the oscillations of *Florisphaera profunda*, *Helicosphaera carteri* and *Braarudosphaera bigelowii* taxa. Reworked coccoliths were used to infer continental runoff (e.g. Bonomo et al., 2016), alongside XRF data (K/Al, Ca/Ti ratios).

One of the principal outcomes of the dataset's analysis is the recording of a marked reorganization in ocean-atmosphere interactions at the transition from the Late Pleistocene to the Holocene, shown by a notable increase in WWG, *F. profunda*, also supported by cluster analysis and changes in elemental ratios (K/Al, Ca/Ti). This shift aligns with rising insolation from 14.3 ka BP, suggesting increased moisture and water column stratification, also seen in Balearic Sea records (Frigola et al., 2008).

The major climatic events recorded include: HS2 (25.8–23.1 ky BP), LGM (23.1–18.5 ky BP), HS1 (17.4–14.3 ky BP), BA (14.3–12.8 ky BP), YD (12.8–11.5 ky BP), the 8.2 ka event, and the Little Ice Age (LIA). During HSs, the coccolithophore assemblages show changes linked to meltwater discharge, which promoted *H. carteri* blooms. LGM and YD intervals recorded increased CWG and placoliths, indicating high productivity under cold, mixed conditions. The BA marks a shift toward oligotrophic, warm-affinity species, particularly *B. bigelowii,* at the onset of Organic Rich Layer 1–like deposition (14.3–8.8 ky BP). Early Holocene warming led to stratified and warmer water conditions highlighted by WWG and *F. profunda*, interrupted by the 8.2 ky event. The LIA is identified at the top of the core by increased runoff due to negative NAO phases (Cascella et al., 2019).

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Paleosol stratigraphy of the Po Plain records Late Pleistocene high-frequency climate oscillations

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Keywords: paleosol stratigraphy, climate oscillations, Bond cycles.

The Late Pleistocene is characterized by climate oscillations at different time scales. Millennial-scale warm-cold oscillations, called Dansgaard-Oeschger (DO) events, punctuated the overall cooling trend from the Last Interglacial (ca. 125 ka BP) to the Last Glacial Maximum (ca. 22 ka BP). DO events are bundled into longer-term cooling cycles, lasting on average 10-15 kyr, with asymmetrical saw-tooth shapes, which culminated in enormous discharge of ice-rafted detritus into the North Atlantic (Heinrich events) (Bond et al., 1993). These high-frequency climate oscillations are recorded in several marine and terrestrial archives (Fletcher et al., 2010).

A suite of aggradationally stacked paleosols from the Po Basin (northern Italy) provides an unprecedent record of environmental changes across the upper part of the Late Pleistocene (MIS 3 and 2) in the Mediterranean region. Individual paleosols are weakly developed and characterized by an upper $CaCO_3$-free (eluvial) horizon overlying a $CaCO_3$-enriched (illuvial) horizon. The analysis of a large dataset of radiocarbon dates, lateral tracking of paleosols and correlation with the pollen record of northern Italy demonstrates that the development and burial of paleosols in the southern Po Plain was mainly controlled by changes in vegetation driven by climatic oscillations at the scale of Bond cycles. Soil horizons started to form at the onset of Bond cycles, when warm climate conditions favored the spread of dense forests, which protected the Apennine drainage basins from erosion, inhibiting sediment production. Soil development was interrupted during cold phases at the culmination of Bond cycles, corresponding to Henrich events H2, H3 and H4, when forest retreats enhanced erosion in the drainage basins and sediment delivery to the alluvial plains. Increased sediment supply promoted the burial of formerly pedogenized surfaces by overbank sedimentation.

The outcomes of this research highlight the potential of alluvial deposits to record past environmental and climate changes. Quaternary paleosol-bearing successions with high chronological constraints can yield insight into the response of alluvial systems to high-frequency climate perturbations, which is crucial under the current scenario of rapid climate change.

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Radiolarian biostratigraphy and geochemistry in the Ypaton Ophiolitic complex (Greece)

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Keywords: ophiolitic mélange, Triassic and Middle Jurassic radiolarians, Ypaton Greece.

In the NE part of Thebes, the Boeotia region of mainland Greece extends the ophiolite complex of the Ypaton area, which represents the southeastward prolongation of the Othris, Kallidromon, and Atalanti ophiolite complexes. The Ypaton ophiolite complex appears tectonically sandwiched between the Pelagonian-derived platform units - which consist of Upper Jurassic neritic limestone bearing Cladocoropsis mirabilis Felix - at the base, while at the top was overthrust by Lower Jurassic neritic limestone bearing Orbitopsella sp. (Ktypas Mountain) during post-late Eocene compressive tectonics.

In this area, seven sections were sampled, and seventeen samples of radiolarian cherts, basalt, and basaltic breccia were collected for radiolarian biostratigraphy and basalt geochemistry. The sampled sections belong to the Sub-ophiolitic Mélange Unit, which consist of continental- and oceanic-derived slices associated with sheared sedimentary deposits (shales, pebbly mudstones, and pebbly sandstones).

The age of radiolarian cherts is referable to the Middle Triassic and Middle Jurassic, in particular samples 13GR81 and 13GR83 are referable to the latest Anisian for the presence of Oertlispongus inaequispinosus Dumitrica, Kozur & Mostler with Paroertlispongus mostleri (Kozur), while samples 14GR5 and 14GR7 are referable to the latest Bajocian-early Bathonian for the presence of Protunuma ochiensis Matsuoka with Hemicryptocapsa tetragona (Matsuoka), and late Bajocian - middle Bathonian for the presence of Unuma gordus Hull with Striatojaponicapsa synconexa O'Dogherty, Goričan & Dumitrica, respectively.

The Triassic rocks are commonly associated with the rift-drift and opening of the Neo-Tethys in the Hellenides (Vardar Ocean). A general evolution from alkaline magmatism toward progressively less enriched P-MORB, E-MORB, and N-MORB from Early to Late Triassic records the basin evolution from continental rift to mature ocean formation. The Jurassic rocks show an evolution from a nascent forearc (N-MORB, MTB, and boninites) to an intra-oceanic arc (boninites and IAT) in a short time span in the Middle Jurassic, followed by the formation of a continental arc (CAB) and an ensialic backarc (BABB) in the Middle-Late Jurassic.

High-resolution quantitative biostratigraphy of planktonic foraminifera from the Early Miocene (ODP Leg 154 Site 926, Ceara Rise, Equatorial Atlantic Ocean)

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Keywords: high-resolution biostratigraphy, planktonic foraminifera, Early Miocene.

During the Early Miocene, the biostratigraphic resolution of planktonic foraminiferal zonations is relatively low, compared to the younger intervals of Neogene, and high-resolution quantitative records of planktonic foraminifera are scarce, especially at low latitudes. In addition, there is an ongoing debate regarding which bioevents best approximate the Aquitanian/Burdigalian boundary. In absence of a formal definition, the Base of the calcareous nannofossil *Helicosphaera ampliaperta* (dated at Ceara Rise at 20.43 Ma) has been provisionally adopted to mark the base of the Burdigalian Stage (e.g., Raffi et al., 2020). Here, the results of a high-resolution quantitative analysis of planktonic foraminiferal assemblages from Site 926 (ODP Leg 154, Ceara Rise) for the interval from 21.5 to 17.6 Ma are presented. Following the astronomically calibrated composite section of Site 926 (Shackleton et al., 1999; Pälike et al., 2006), samples were selected from nannofossil-foraminiferal chalk levels with a time resolution of ~30 kyr. This study provides the quantitative distribution patterns of the biostratigraphic marker species of the studied interval and allows the refinement of the stratigraphic position and age of the main bioevents. Age calibration of some identified bioevents, such as Top (T*) Paragloborotalia pseudokugleri*, Base (B) *Globigerinoides altiaperturus*, B *Globigerinatella* sp. and B *Globorotalia praescitula*, is in good agreement with the current biochronology (Raffi et al., 2020). Conversely, T *P. kugleri* appears younger than what reported in literature, postdating B *H. ampliaperta*. Notably, the age calibration of T *P. kugleri* and B *G. altiaperturus* closely aligns with the age of the top of magnetic polarity Chron C6An (19.97 Ma), possibly offering new perspectives on the selection of criteria for defining the base of the Burdigalian Stage. Further identified events, Top common (Tc) *Paragloborotalia kugleri*, Tc *Tenuitella munda*, T *Globorotalia mendacis* and T *Ciperoella fariasi*, enhance the biostratigraphic resolution of the studied interval. Finally, quantitative records of other biostratigraphic markers, such as *Catapsydrax dissimilis*, *Paragloborotalia siakensis*, *P. birnageae*, *P. nana*, *Trilobatus trilobus* gr. and *Globigerinoides parawoodi* gr., reveal details of their distribution pattern within the studied interval. Biostratigraphic correlation of Site 926 with other low-latitude (I)ODP Sites is hampered by inconsistencies in the relative stratigraphic positions of T *P. pseudokugleri*, T *P. kugleri* and calcareous nannofossil events, partly due to different resolution of the biostratigraphic analysis and partly due to the absence of important events (e.g., *B Globigerinatella* sp., B *H. ampliaperta*, *Helicosphaera euphratis/H. carteri* crossover) at some of the considered sites. Overall, these results may contribute to improving the biostratigraphic resolution and the accuracy of Early Miocene standard zonation.

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Integrated biostratigraphy of condensed pelagic deposits from Sant'Angelo Romano (Cornicolani Mts., Italy)

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Keywords: biostratigraphy, ammonites, pelagic carbonate platforms.

We present an integrated sedimentological and biostratigraphic study of a condensed Jurassic deposit exposed in the Cornicolani Mountains at Sant'Angelo Romano, on the southern margin of the Sabina Plateau (central Italy). These low hills, a few kilometres east of Rome, rise from the Acque Albule plain between the Aniene and Tiber valleys.

Despite longstanding geological interest in this area, the palaeontological and biostratigraphic potential of the condensed pelagic successions in the Cornicolani has remained largely unexplored, and these successions have long been only object of the interest of collectors.

Fieldwork and laboratory analyses, including macrofaunal identification and microfacies examination of thin sections, reveal a condensed succession of the Pelagic Carbonate Platform (PCP) type. It consists of hazel-coloured packstone–wackestones rich in ammonites, brachiopods, crinoids, radiolarians, and sponge spicules, assemblages typical of pelagic environments. The stratigraphic and palaeontological data allow attribution of the deposit to the *Calcari nodulari dell'Infernaccio*, the lowermost unit of the Bugarone Group. Biostratigraphic analysis and taxonomic identification of ammonite and brachiopod taxa allowed to place the studied outcrop within the *Naumachensis* Horizon of the *Emaciatum* Zone, corresponding to the Upper Pliensbachian. These results overall help refine the palaeobathymetric and palaeoenvironmental reconstruction of the Sabina Plateau, highlighting its role as a structural high within a broader pelagic basin that underwent significant differentiation following the Early Jurassic rifting events.

Benthic foraminifera as a tool to investigate timing, causes and ecosystem response to the end-Triassic extinction

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Keywords: biostratigraphy, Triassic/Jurassic boundary, Lazarus taxa.

The end-Triassic extinction (ETE) is one of the five big extinctions of the Phanerozoic. It was likely caused by enhanced volcanic activity in the Central Atlantic Magmatic Province (CAMP), which initiated the breakup of the Pangea supercontinent.

During the ETE, carbonate platform biocalcifiers, including involutinid benthic foraminifera, experienced high extinction rates that have been linked to volcanically-induced global changes in climate and carbon cycle. Most studies focused on the classical sections of the Northern Calcareous Alps (NCA, Austria) and Lombardy Basin (Italy), where the extinction of benthic foraminiferal assemblages of the Rhaetian *Triasina hantkeni* Zone and the aragonitic Dachstein-type biota coincides with the demise of the carbonate platform, possibly due to relative sea-level change and/or ocean acidification (Galli et al., 2007; McRoberts et al., 2012). Extinctions in these sections also coincide with the initial negative carbon isotope excursion (CIE), which has been linked to the earliest major CAMP erupting phase (e.g., Hesselbo et al., 2002).

In this study, we present a detailed bio- and carbon-isotope stratigraphy of three Southern Tethyan carbonate platform sections, Mt. Messapion (Greece), Valle Agricola and Mt. Sparagio (southern Italy). These sections show persisting carbonate productivity across the Triassic/Jurassic boundary, potentially preserving a more complete record of the ETE in these ecosystems.

In the studied sections, the disappearance of the *Triasina hantkeni* assemblage is observed within a positive $\delta^{13}C_{carb}$ excursion that, according to our study, correlates with that documented in the Schattwald beds (NCA) and Malanotte Fm (Lombardy Basin) above the initial CIE. This level represents the true extinction of the carbonate platform biota, while its earlier disappearance in the Northern Tethyan sections of the NCA and Lombardy Basin likely represents a pseudoextinction due to the carbonate platform demise. This conclusion rules out changes in climate and the carbon cycle linked to the earliest CAMP erupting phase as the cause of the extinction of the Rhaetian carbonate platform biota (Montanaro et al., 2024). Despite extinctions, Southern Tethyan carbonate platform ecosystems adapted to environmental disturbances through a shift in the dominant carbonate production style from aragonitic biocalcification to chemical and microbially-mediated $CaCO_3$ precipitation. The ecosystem recovery was very slow, characterized by the reappearance of Lazarus taxa among agglutinated benthic foraminifera after some million years in the Hettangian, followed by the evolution of new aragonitic biocalcifiers (dasycladacean algae) during the early Sinemurian.

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Calcareous nannofossil paleofluxes as proxies of coccolithophore production and calcification: Insights into the Albian-Cenomanian Tethys Ocean

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Keywords: nannofossils, paleofluxes, Cretaceous.

Among the strategies proposed to mitigate accelerated climate change, Ocean Alkalinity Enhancement aims to replicate natural processes to increase the CO_2 storage capacity of the ocean, but the potential efficiency and impact on marine phytoplankton, including coccolithophores, is largely unknown. Therefore, natural analogs in the geological past may have the potential to clarify longer-term responses.

We focused on the quantification of nannofossil calcite paleofluxes to understand the response of coccolithophores to different marine carbonate chemistry that influenced the absorption of atmospheric CO_2 into the oceans. The investigation was carried out for the Upper Albian-Lower Cenomanian interval of the Piobbico Core-Monte Petrano composite section (Umbria-Marche Basin, Italy), consisting of pelagic marlstones and marly limestones (Marne a Fucoidi) overlain by limestones (Scaglia Bianca). High-resolution integrated biostratigraphy, chemostratigraphy and cyclostratigraphy allowed accurate estimates of sedimentation rates.

Calcareous nannofossils were quantified in ultrathin sections by counting all specimens observed in 1 mm^2. Total nannofossil calcite paleofluxes were gathered based on absolute abundances and volume/mass of individual taxa in a unit area (1 mm^2) and unit time (1 year).

Out of 36, only 10 genera constitute 95% of nannofossil assemblages. The amount of biogenic calcite produced by individual nannofossil taxa is highly variable and strictly dependent on the ultrastructure and dimensions. Therefore, some genera were separated into morphometric groups to calculate paleofluxes with highest accuracy. *Watznaueria barnesiae* dominates the nannofloral assemblages in the investigated interval, with abundances fluctuating from 44% to 70%. *Nannoconus* abundance is very variable, reaching relatively high paleoflux values in the lower portion of the Scaglia Bianca.

Lithostratigraphically, the boundary between the Marne a Fucoidi and the Scaglia Bianca does not correspond to a shift in nannofossil paleofluxes: an increase has been observed in the transitional interval where the terrigenous input starts to decrease.

The results show that nannofossil absolute abundances, calcite paleofluxes and $CaCO_3$ content are not directly correlated and that a sedimentation rate normalization is crucial to derive total assemblages and single taxa behavior. Paleoenvironmental changes in temperature, fertility, chemistry impacted calcareous nannoflora with species-specific responses. Overall, the data show that a relatively high terrigenous input (Marne a Fucoidi) limited coccolithophore biocalcification. At times without terrigenous input (Scaglia Bianca), fluctuations in nannofossil calcite paleofluxes suggest a potential controlling role of alkalinity, which may have differentially affected single species/genera. Thus, it is possible that individual taxa had maximal calcification at specific (optimal) alkalinity values.

Virtual 3D models as an additional tool for the planktonic foraminifera biostratigraphy in thin sections: the case derived from the survey of the Sheet "404" Isernia (CARG Project)

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Keywords: planktonic foraminifera, thin section, 3D model.

In the framework of the ongoing geological sheet n. 404 "Isernia", scale 1:50 000, for the CARG Project, an integrated study was conducted in collaboration between DiSt, DiBT and DiSTAR Departments in order to better define the lithostratigraphic and biostratigraphic characteristics of the formations recognized during the field survey. In this way, the chronostratigraphic ranges of the lithostratigraphic units can be attributed as best as possible. The segment of the Appeninic chain enclosed in the Isernia sheet shows a platform-to-slope complex transition, well documented in the Matese Mountain, Montagnola di Frosolone and Venafro Mountains.

74 thin sections (TS) were prepared by calcareous or marly rock samples coming from the Coste Chiavarine Formation (CCH, Cenomanian *p.p.* - Campanian), Monaci Formation (FMO, Middle Eocene *p.p.*), Macchiagodena Formation (GOD, Oligocene to Middle Miocene), Monte Crivari polygenic calcirudites and calcarenites (RIV, ?Oligocene-Middle Miocene) and Longano Formation (LNG, Middle-Late Miocene). Special emphasis was assigned to the analysis of planktonic foraminifera, crucial tool for biostratigraphy and dating of the slope deposits. The 2D views of planktonic foraminifera have notoriously inherent limitations that can obscure critical morphological details, potentially leading to ambiguous interpretations. Therefore, a comparative analysis between TS images and 3D models has been tested, but only for five Miocene planktonic foraminiferal genera: *Dentoglobigerina, Fohsella, Globorotalia, Orbulina*, and *Trilobatus*. These genera were selected for their availability in 3D format in the literature, biostratigraphic relevance and distinctive morphologies. Up to now, 3D models of Cretaceous and Paleogene morphotypes are not available, yet. Virtual sections obtained by the 3D models of the above mentioned genera were performed to replicate the cuts in TS, enabling a direct and detailed comparison of foraminiferal tests. The interactive 3D models may overcome many of the intrinsic limitations of traditional TS by the rotation and examination of specimens from multiple perspectives. This approach appears to improve the visualizations of morphological characters of the tests and help in species identification, by revealing of diagnostic morphological features that are often obscured or ambiguous in the 2D views. Even though the experiment is now only applicable for some Miocene morphotypes, it has the potential to improve significantly the identification of planktonic foraminifera in thin sections and as consequence, to define the biozones and relative ages of the geological units.

Bio-Chronostratigraphy and Facies character of the Upper Cretaceous carbonates of the Coste Chiavarine Formation in the north Venafro Mountains (Central Apennines, Italy)

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Keywords: Upper Cretaceous carbonates, microfacies analysis, Southern Apennines.

This study focuses on the microfacies and the micropaleontology of the Upper Cretaceous Coste Chiavarine Formation (CCH Fm), exposed in the northern Venafro Mountains (Central Apennines) and currently under investigation within the geological sheet n.404 "Isernia" at 1:50.000 scale (CARG Project). The formation, dated no older than Late Cenomanian, was sampled at metre scale in Colle Mastroleoni's area (Montaquila, Isernia), where 21 samples were collected from whitish to light brown, fine-grained, interlayered calcarenites and carbonate mudstones.

Field observations were integrated with petrographic and micropaleontological analyses of thin sections, aimed at refining the stratigraphy of the CCH Fm and its transition to the overlying Maastrichtian Monte Calvello Formation (VLO Fm).

Special attention was paid to the identification of key microfossils -though poorly preserved- including planktonic and benthic foraminifera, calcareous algae, and the recognition of diagnostic features such as recrystallization patterns, cements, and dolomitization.

Two main microfacies types were identified. CCH-MF1 consists of burrowed mudstone to wackestone with planktonic foraminifera (globotruncanids, heterohelicids), calcispheres, and mollusk/echinoderm debris. It may appear as diffuse patches or mm-scale lithoclasts. CCH-MF2 comprises poorly washed grainstone-packstone, rich in µm-scale rudist debris (mainly radiolitids), echinodermal fragments with distinctive syntaxial overgrowth cements, and reworked shallow-water benthos. Common components include fragmentary thaumatoporellids, miliolids, peneroplids, textulariids, nubeculariids, possible nezzazzatids, and cuneolinids. Occasional sponge debris and chert are also found. These facies often show lamination and widespread recrystallization/ dolomitization, expressed by scattered euhedral–subhedral planar-e dolomite crystals, at times clustered in a fabric-destructive mosaic. CCH-MF1 reflects background pelagic sedimentation in a gentle slope to basin setting, whereas CCH-MF2 is interpreted as the product of episodic gravity flows and redeposition events. The transition to the VLO Fm is gradational, characterized by coarser deposits, more abundant rudist fragments, and poorer sorting, suggesting a shift toward a Maastrichtian slope enscarpment.

Despite the limited preservation, the planktonic foraminiferal assemblages (*Marginotruncana*?, *Contusotruncana*, *Globotruncana*, *Globotruncanita*) would constrain the age of the CCH Fm to the Campanian. Reworked benthos, including thaumatoporellids, miliolids, nubeculariids, *Cuneolina pavonia*, *Accordiella conica*,*?Montcharmontia apenninica*, and *Orbitoides/Lepidorbitoides* spp., support this interpretation and suggest dismantling of an Upper Cretaceous "Senonian" platform margin and interior.

This study provides an updated stratigraphic interpretation of the CCH Fm and enhances understanding of the Late Cretaceous depositional dynamics in the Molise sector of the Central Apennines.

A multi-isotopic study of conodonts to uncover the Sr and Ca isotopic balance of the Ocean: application to the latest Devonian

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Keywords: Conodonts, Sr isotopes, Ca isotopes.

The radiogenic strontium isotope ratio ($^{87}Sr/^{86}Sr$) preserved in the marine fossil record reflects changes in the $^{87}Sr/^{86}Sr$ composition of the Phanerozoic ocean. This ratio has long been a fundamental tool in chemostratigraphy, as its variations provide insights into the evolving balance of weathering inputs from different rock types, such as ancient continental crust, mantle-derived rocks, and sedimentary carbonates. In addition to radiogenic Sr, stable isotope ratios of strontium ($\delta^{88}Sr$) and calcium ($\delta^{44}Ca$) offer complementary constraints on the sources of these elements to the ocean. They also provide a means to explore the role of global carbonate production, which represents the primary sink for both Sr and Ca in the marine system.

In this study, we explore the application of a multi-isotopic approach on conodonts from the latest Devonian of the Kowala quarry in central Poland. The studied interval precedes the Hangenberg event, a global climatic perturbation and second-order mass extinction event that marks the Devonian-Carboniferous boundary. Sample sets from three different conodont genera have been measured for $^{87}Sr/^{86}Sr$, $\delta^{88}Sr$ and $\delta^{44/40}Ca$, along the studied interval. Conodont $^{87}Sr/^{86}Sr$ ratios are coherent between the different genera and record a general decreasing trend throughout the interval, aligning well with previously published data. $\delta^{88}Sr$ values of the genus *Branmhela* are systematically lower by approximately −0.2‰ compared to the other two genera, although they exhibit similar relative trends. This pattern suggests a significant biogenic influence on conodont $\delta^{88}Sr$ values, while still preserving the potential to reflect relative environmental variations. In agreement with previous studies, we report no measurable difference in $\delta^{44/40}Ca$ values between the three conodont genera. The $\delta^{44/40}Ca$ stratigraphic trend, only investigated in *Palmatolepis,* shows a transient decrease of ~ 0.1‰ in the *ultimus* zone following the deposition of the regional Kowala black shale.

A multi-proxy approach to unravel palaeoenvironmental variations at subannual scale: the ADA270 ice core (Adamello Massif, N Italy)

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Keywords: dust, pollen, Sahara.

Temperate glaciers are often considered poor climate archives because of ice fusion and water percolation in the warmest months of the year; these phenomena cause partial to total loss of the chemical signal in ice. However, thanks to their grain size, insoluble particles are often well preserved and can be used for palaeoclimate reconstructions.

The Adamello Glacier (46° 09' N, 10° 32' E) is located on the southern slopes of the European Alps (Italy), at an altitude between 2560 and 3420 m a.s.l.; it is considered a temperate glacier. In 2021, a 224 m long ice core was drilled in the Pian di Neve, the summit plateau of the Adamello Glacier. In this sector of the glacier, the ice has an accumulation rate of ca 0.9 m/year. The annual signal is constituted of ca 2-10% in ice thickness by dark spring/summer layers rich in insoluble particles, while the remnant of the yearly signal is composed of autumn-winter clear ice, almost devoid of particles. The spring/summer layers are very rich in biotic proxies. For this study, eight different types of particles are investigated contemporaneously: pollen, diatoms, fern and fungi spores, charcoal fragments, phytoliths, sponge spicules, and green algae. So far, 143 samples have been examined, for a total of ca 60,000 objects identified and subdivided in the various proxy classes.

Each proxy presents its own pattern, but it is from the combination of all the proxies that two different sources of paleoenvironmental signals can be identified: a medium-distance extralocal component, mainly constituted by pollen and spores from the woodlands downhill from the glacier, and a long-distance component represented by Saharan Dust events. The combination of these components creates unique features for each year so that events like wildfires or deposition of Sahara Desert dust can be traced and used both to reconstruct environmental and climate changes, and to refine the ice core chronology.

Living foraminifera of the Marano and Grado lagoon (Northern Adriatic Sea, Italy): relationships with key ecological features and tools for biomonitoring

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Keywords: foraminifera, environment, bioindicators.

Lagoons are distinctive natural ecosystems with a delicate biological balance hosting a wide range of organisms. They represent transitional water environments (TEs), including fjords, deltas, and estuaries, where fluctuations in salinity, oxygenation, nutrients, and other factors produce a complex degree of confinement from marine waters.

In recent decades, these ecosystems have been heavily exploited by humans, with negative effects on the aquatic ecosystem. By studying the biological consequences, which affect both animal and plant species, we can discover biotic indicators that can detect changes due to human activity. The increasing interest in benthic foraminifera as bioindicators in marine environments has led to a growing interest in their role also as bioindicators in TEs (Bouchet et al., 2021).

The high variability of environmental conditions in lagoons induces natural stress that is reflected in low-quality ecological indices, despite the environment being in good condition. This is the so called "estuarine quality paradox" (i.e., Elliott & Quintino, 2007). One of the challenges is to identify the stress induced by the natural environment and to distinguish it from stress related to human influence.

The Marano and Grado (MG) Lagoon is a 160 km² shallow coastal water system situated in the northern Adriatic Sea in Italy, positioned between the deltas of the Tagliamento and Isonzo rivers. This lagoon is generally considered a well-preserved area where environmental conservation must co-exist with many human activities, including fishing, clam harvesting, shipping, and industry. The MG Lagoon, particularly in the eastern area of Grado, is known for historical mercury (Hg) contamination from the Idrija Hg mine in Slovenia through the Isonzo River inputs. In addition, a more recent source of contamination has been recognized in the decommissioned chlor-alkali plant of the Torviscosa industrial complex (Italy) (Acquavita et al., 2012).

This research presents one of the first study on living foraminifera of the Marano and Grado Lagoon. *Ammonia tepida*, *H. germanica*, *A. perlucida* and *C. gunteri* are the most characteristic taxa, exhibiting a positive correlation with the total organic carbon content. Other species such as *A. parkinsoniana*, *Quinquelculina* spp. and the agglutinated taxa exhibit a stronger association with salinity. Foraminifera exhibit a tendency for shell deformation, which is most noticeable in *Ammonia* spp. and *C. gunteri*. The cluster analysis evidenced three main assemblages: urban (*Haynesina germanica* as dominant species), inner (*H. germanica* with *Aubignyna perlucida* dominant) and the outer lagoon (*A. parkinsoniana* dominant) biotopes. The internal sectors of the lagoon exhibit diminished environmental quality, whilst the outer biotopes are characterised by higher biotic indices and a reduced prevalence of species that are more tolerant to chemical and physical variations in the environment.

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Correlation between Norian/Rhaetian boundary and paleoenvironmental events from high-resolution biostratigraphy and chemostratigraphy in the Sasso di Castalda section, Lagonegro Basin, Southern Italy

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Keywords: Norian/Rhaetian boundary, Late Triassic, carbon-isotope.

The Late Triassic was a period of catastrophic environmental change and stepwise biotic turnovers. The Norian/Rhaetian boundary (NRB; ~205.7 Ma) is particularly marked by faunal turnovers such as ammonoids, conodonts, and radiolarians, as well as carbon cycle may have perturbed at the NRB (e.g. Rigo et al., 2020). Several possible causes for the faunal turnovers and environmental perturbations across the NRB have been discussed, including the volcanic activity of the Central Atlantic Magmatic Province and the Angayucham Terrane, and an impact event related to the Rochechouart crater (e.g. Rigo et al., 2020). However, relationship between the faunal turnovers and the known geologic events remains poorly understood, due to lacking the high-resolution chemostratigraphy and biostratigraphy. Here, we present the high-resolution radiolarian and conodont biostratigraphy and stratigraphic variations in whole-rock major and trace element concentrations, together with organic carbon-isotope, across the NRB in the Sasso di Castalda section, belonging to the Lagonegro Basin, Southern Apennines, Italy. In our biostratigraphic analyses, according to the radiolarian zonation by Carter (1993), the uppermost Norian to lowermost Rhaetian radiolarian assemblages, *Betraccium deweveri* (U.A.1), and *Proparvicingula moniliformis* (Assemblage 1, U.A.2-5, and Assemblage 2, U.A.6-23) Zones were recognized in the study section. In addition, we constrained the position of the NRB in the Sasso di Castalda section based on the First Appearance Datum of conodont *Misikella posthernsteini* s.s. Our study of major and trace element concentrations revealed the presence of a red shale with anomalous siderophile elements just above the platinum group elements-enriched black shale reported in the previous study (Sato et al., 2021). Based on our conodont biostratigraphy and the previously-reported magnetostratigraphy (Maron et al., 2015), the depositional age of the siderophile elements-enriched layer was estimated to be during the latest Norian (ca. 205.7-207.8 Ma). This age is consistent with the reported radioisotopic age for the Rochechouart crater (206.92±0.32 Ma), suggesting that the Rochechouart impact is the source of the siderophile elements. Our weathering proxy data (Chemical Index of Alteration; CIA, Weathering Index of Parker; WIP) indicate that the chemical weathering intensified prior to the NRB. Seawater Os isotope ratios ($^{187}Os/^{188}Os$) reported from the Sasso di Castalda section show an increasing trend in the uppermost Norian (Sato et al., 2021), supporting enhanced continental weathering. In addition, massive input of light carbon isotopes might have occurred at the NRB, as suggested by negative carbon-isotope excursion with an amplitude of ~8 ‰ across the NRB. During this interval, the 187Os/188Os ratios decreased and gradually recovered to background levels inferred from the upper Norian sediments (Sato et al., 2021). These findings suggest that potential linkage between extinctions around the NRB and LIPs.

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Reevaluating the link between the Carnian Pluvial Episode and the Wrangellia-Sambosan Large Igneous Province

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Keywords: Late Triassic, Carnian Pluvial Episode, Large Igneous Province.

The Carnian Pluvial Episode (CPE) represents a major environmental perturbation and biotic crisis during the Late Triassic, characterized by intensified precipitation and and major extinctions of marine taxa. The CPE is thought to have been caused by a large igneous province (LIP) magmatism that resulted in the eruption of the Wrangellia flood basalts (FB) in northwestern Canada. In addition to the Wrangellia FB, Carnian oceanic basalts of an intraplate origin, including oceanic seamounts and plateaus, have been recognized in the Jurassic accretionary complex of the Sambosan Belt, Japan. These Carnian basalts originated in an open-ocean realm of the Panthalassa Ocean on the Izanagi Plate and were accreted along the East Asian subduction zone during the Late Jurassic. The contemporaneous emplacement of oceanic and flood basalts in the Sambosan and Wrangellia may suggest a single LIP origin for these basalts. Here, we present new geochemical (major and trace elements) and isotopic (Nd, Pb, and Sr) data to constrain the origin of the basaltic rocks of the Sambosan Belt.

Discrimination diagrams based on least mobile elements suggest that the Sambosan basalts are analogues of the Within Plate Basalts (WPB). In the Nb/Yb-TiO2/Yb diagram, these basalts lie mainly within an OPB array with high TiO2/Yb and Nb/Yb ratios, suggesting that these basalts are derived from a LIP magmatism. Based on the REE composition, the Sambosan basalts are classified into a light rare earth element (LREE)-enriched group (Type1; (La/Sm)n = 2.1-3.3) and a relatively LREE-depleted group (Type2; (La/Sm)n = 0.7-1.3). The (La/Sm)n-(Gd/Yb)n data of the Type2 basalts were formed by up to 5 % melting of garnet lherzolite with a primitive mantle composition, whereas the data for the Type1 basalts are plotted along the garnet melting curve and these degrees of partial melting were 1%-5%, similar to that of typical ocean island basalts.

The Sr and Nd isotopic compositions of the Sambosan basalts indicate that they were formed from a depleted mantle source with no contribution from delaminated lower continental crustal material or recycling of subducted continentally derived sediments. In the 206Pb/204Pb-207Pb/204Pb diagram, most of the Sambosan basalts and the Wrangellia FB lie above the NHRL (North Hemisphere Reference Line). In addition, portions of these basalts have Pb isotopic compositions plotting on or near the 4.43 Ga geochron (age corrected to 230 Ma) with depleted Nd isotopes and TiO2 concentrations, which are consistent with the composition of an early depleted, non-chondritic reservoir. High 206Pb/204Pbt and 207Pb/204Pbt ratios with the occurrence of xenocrysts trapped by recycled mantle components of the Sambosan basalts could indicate the involvement of the recycled oceanic crust (such as HIMU origin).

The similarity of the isotopic compositions of the Sambosan basalts and the Wrangellia FB suggests that these basalts were derived from a single LIP magmatism associated with a mantle plume source in a mid-oceanic setting of the Panthalassa Ocean in the Carnian. The geochemical characteristics of most of the Sambosan and Taukha basalts are consistent with emplacement from a plume-associated mantle source in a mid-oceanic setting, and the timing of basaltic volcanism in the Sambosan and Taukha belts is constrained to Ladinian? to upper Carnian. The contemporaneous emplacement of oceanic and flood basalts in the Sambosan Belt and Wrangellia suggests the existence of a Carnian LIP in the Panthalassa Ocean, which likely played a key role in driving the environmental perturbations associated with the CPE.

A high-resolution carbonate $\delta^{13}C$ record of the onset of the Carnian Pluvial Episode (Upper Triassic)

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Keywords: carbonates, stable isotopes, Triassic.

The Carnian Pluvial Episode (CPE) is a climatic perturbation that significantly impacted Late Triassic ecosystems. It was possibly triggered by volcanic eruptions of the Wrangellia LIP and is associated with multiple perturbations of the carbon cycle, evidenced by negative excursions in the carbon isotope record of marine carbonates, terrestrial plants, and bulk organic matter worldwide.

In the Southern Alps of northern Italy, the carbon isotopic signature of the CPE has so far only been recovered from organic matter. Attempts to identify the typical negative carbon isotope excursions in marine carbonates have been hindered by their pervasive diagenetic overprint.

A continuous core, ca. 100 m long, was drilled in marlstones of the basinal San Cassiano and Heiligkreuz formations at Lago d'Antorno near Misurina (Belluno). The core intercepted the last calciturbidites that testify for active carbonate production associated with the nearby Lower Carnian microbial-skeletal carbonate platforms (Cassian dolomite), before their death that coincides with the CPE.

Stable carbon isotope measurements of the carbonate fraction in marlstones were accompanied by careful study of thin sections and SEM, EDS chemical analyses, and XRD of selected samples to provide a petrographic background for interpreting $\delta^{13}C$. A subset of samples was also washed, and the residuals were observed under a binocular microscope.

Carbonate is present throughout the succession as fine particulate and small skeletal grains. Calcispheres (calcareous nannofossils attributed to genus *Orthopithonella*) are also present but are never abundant. Cements occur associated with large carbonate grains, e.g., within mollusk shells, and include high-Mg dogtooth cement rims, isolated siderite rhombohedra, rims and mosaic cavity-filling ferrous calcite. These cements are associated with ubiquitous pyrite, mostly forming framboids. Most of the cements are precocious, and the original mineralogy of aragonitic or high-Mg calcitic skeletal grains is typically preserved within the marlstones.

By analyzing the mineralogical composition of selected samples, and by separating and analyzing skeletal grains from washed residues, it was possible to tentatively attribute an isotopic signature to specific particulate and cement components. This approach served as a guide to clean the core record from samples that were more likely to be contaminated by secondary carbonate. Only those samples that most likely contain pristine marine carbonates were therefore retained. The resulting $\delta^{13}C$ curve exhibits multiple carbon isotope excursions, ca 2‰ wide, that we interpreted as a reliable record of a complex perturbation of the carbon cycle at the onset of the CPE.

Last-century variability in North Atlantic water masses and temperatures inferred from cold-water coral chemistry

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Keywords: cold-water corals, water masses, temperatures.

The aragonitic skeletons of cold-water corals (CWCs) provide high-resolution archives of physico-chemical changes in intermediate-depth water masses, capturing environmental variability on sub-decadal timescales. Previous research has demonstrated that variations in seawater temperature, water mass ventilation age, and provenance can be reconstructed using skeletal geochemical proxies such as Li/Mg ratios, paired U/Th and radiocarbon (^{14}C) dating, and neodymium (Nd) isotopes. Among CWCs, the solitary azooxanthellate scleractinian coral *Desmophyllum dianthus* is particularly valuable due to its wide distribution, longevity (spanning up to a century), and layered skeletal growth, which enables fine-scale temporal resolution of geochemical analyses. In this study, we investigated multiple *D. dianthus* specimens collected in 2012 from the Northern Iceland Basin (570–700 m depth) during the ICE-CTD expedition aboard the R/V *Thalassa*, using the IFREMER-operated remotely operated vehicle (ROV) Victor 6000. Subsamples taken along the growth axis of the coral skeletons were analyzed for Li/Mg ratios, stable isotopes ($\delta^{11}B$, $\delta^{18}O$, $\delta^{13}C$), U/Th and ^{14}C dating, as well as Nd isotopic compositions. The aim was to reconstruct changes in temperature and water mass provenance in North Atlantic intermediate waters, focusing specifically on Iceland-Scotland Overflow Water (ISOW), Sub-Arctic Intermediate Water (SAIW), and Western North Atlantic Central Water (WNACW), and to assess how their relative contributions have evolved over the past century. The Li/Mg ratios provided sub-decadal temperature records, showing variations between ~2 to ~6 °C, closely linked to changes in Nd isotopic compositions. These findings can be explained by decadal fluctuations in the North Atlantic Oscillation and East Atlantic atmospheric patterns, which influence the strength of the Atlantic Subpolar Gyre, leading to changes in the amount of warmer Subtropical Gyre-sourced water or colder Subpolar Gyre-sourced water. Additionally, our results suggest a significant reduction, by about half over the past ~70 years, of the ISOW, pointing to an increased northward transport of warm subtropical waters in recent decades. This shift may have contributed to the recent warming in the Arctic region and a notable multi-decadal weaking of the Nordic Sea overflow currents.

Osmium isotope and highly siderophile element profiles across the Cretaceous/Paleogene boundary in the western Pacific Ocean

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Keywords: K/Pg boundary, Re-Os isotopes, Pacific Ocean.

The delivery of highly siderophile elements (HSE) to the ocean by the Cretaceous/Paleogene (K/Pg) asteroid impact has been recorded globally as HSE enrichments and negative osmium isotope (187Os/188Os) excursion from steady state (~0.4) to < 0.2 in marine sediments (Ravizza & Peucker-Ehrenbrink, 2003; Ravizza & VonderHaar, 2012; Sato et al., 2025). The reconstructed marine Os isotope curves can be used for global age correlations of K/Pg sediments and as an Os isotope-based geochemical clock to trace the early Paleocene on the ~10 thousand years (kyr) scale. However, this approach has been established with data from only two distal sites, the South Atlantic and the Southern Ocean (Ravizza & VonderHaar, 2012). Here, we present new records of 187Os/188Os and HSE abundances across the K/Pg boundary in the pelagic red clay recovered from the piston cores of KR13-02 PC05 around Minamitorishima Island in the western Pacific Ocean. The anomalously high HSE abundances (~15 ppb Ir) and the lowest 187Os/188Os ratios (~0.14) were identified at ~9.95 meters below sea floor (mbsf) as the position of the K/Pg boundary (~66.001 Ma; Gradstein et al., 2020). We also recognized the two magnetic reversal boundaries above and below the K/Pg horizon, which we attribute to C29n/C29r (65.700 million years ago (Ma)) at ~95 cm above and C29r/C30n (66.380 Ma) at ~5 cm below the K/Pg (Gradstein et al., 2020). The age of each sample in the Paleocene red clay was estimated from average sedimentation rates constrained by the stratigraphic thickness between the defined K/Pg boundary and the two magnetic reversal boundaries.

The HSE concentrations in the Paleocene red clay at the study site gradually decrease upward through the sediments, but remain high (1–10 ppb) up to 50 cm above the K/Pg boundary. In addition, the relatively high concentrations of HSE (> 1 ppb) were also detected until ~5 cm below the K/Pg boundary. These results suggest that the record of HSE abundances at the study site may be biased by reworked impact-derived materials.

The age-corrected $^{187}Os/^{188}Os$ ratios show a gradual increase with some fluctuations, but the ratios recover to only ~0.3 about 300 kyr after the impact. The result of the recovery time scale for the Pacific site is significantly longer than that of the distal sites reported in the previous study (~200 kyr). Although the seawater Os isotope recovery curve at the study site cannot be drawn without evaluating the effect of reworking, the period of low $^{187}Os/^{188}Os$ ratios extends well beyond the extent of the HSE enrichments. This indicates that the hydrogenous component dominates the sedimentary budget at least after ~50 cm above the K/Pg boundary, implying a distinct Os isotope recovery time scale between the Atlantic and Pacific Oceans. To confirm the versatility of the post-impact Os isotope clocks, further research on Os isotope at different sites are clearly needed.

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Geochemical constraints on the trophic level of latest Devonian conodonts

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Keywords: Conodonts, diet, isotopes.

Conodonts are an extinct clade small jawless early vertebrates that played a key role in marine ecosystems from the Early Cambrian to the Early Jurassic, spanning over 300 million years of evolutionary history. Their fossil record is rich, primarily due to their bioapatite dental elements, which are among the most abundant vertebrate remains in carbonate sediments. Conodonts display high morphological diversity and rapid evolutionary turnover, together with a global distribution, all of which make them prime biostratigraphic markers. The disappearance of conodonts marks a major biological transition, so prominent that a large part of the Phanerozoic has been informally referred to as the "Conodontozoic." Beyond their utility in biostratigraphy, conodonts can be valuable geochemical archives. Their composition allows conodonts to serve as proxies for reconstructing environmental and climatic conditions throughout Earth's history. However, despite their relevance, substantial gaps remain in our understanding of their ecology.

Morphological and rare soft-tissue evidence suggest conodonts were active swimmers, with anatomical features such as developed eyes, V-shaped myomeres, and tail fins consistent with life in the photic zone. The presence of conodont remains in coprolites further confirms that they were prey for a wide range of marine predators, indicating their fundamental role in food webs. The trophic level of conodonts has been investigated using Ca isotopes ($\delta^{44/42}$Ca). Assuming Ca isotope fractionation similar to elasmobranchs, conodonts have been suggested to be first-level consumers. Recent studies showed stable Sr isotopes (δ^{88}Sr), in combination with $\delta^{44/42}$Ca, as a promising tool to decipher the relative trophic position of modern terrestrial Mammals and Diapsides. Given their large morphological diversity, did all conodonts share the same trophic position, or did it change through the numerous biological crisis they witnessed?

Herein we present the new δ^{88}Sr and $\delta^{44/42}$Ca data from three latest Devonian genera, that are *Palmatolepis*, *Bispathodus* and *Branmehla,* collected from the Holy Cross Mountains, and investigate the relationship between the conodont geochemical record and their morphology. The δ^{88}Sr value of *Branmehla* shows marked differences compared to those of *Palmatolepis* and *Bispathodus*. While differences in habitats cannot be ruled out, the observed isotopic variations among coeval taxa, combined with morphological distinctions in their P1 elements, suggest that δ^{88}Sr may reflect differences in ecological behaviour. These findings support the potential of δ^{88}Sr as a valuable proxy for inferring feeding strategies in conodonts, consistent with the interpretation of P_1 elements as functionally analogous to teeth, shaped by dietary preferences.

$\delta^{13}C_{org}$ and radiolarian and conodont biostratigraphic records across the Norian-Rhaetian boundary in the Panthalassic pelagic sections from Japan

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Keywords: Late Triassic, Norian/Rhaetian boundary, chert.

The Rhaetian stage of the Triassic was characterized by intense biological, climatic, and environmental changes, ending with the break-up of the supercontinent Pangaea and the end-Triassic mass extinction (ETE). Recent developments in marine biostratigraphy and magnetostratigraphy allow a more detailed sequence of extinctions within major marine groups during the Norian/Rhaetian boundary (NRB). The chronology of the Rhaetian pelagic sediments in the Panthalassic Ocean is based on radiolarian biostratigraphy, which are well established in the Upper Triassic bedded chert successions in Japan (e.g., Sugiyama, 1997). Although recent calibrations of the chronostratigraphic stages and substages in the Triassic are based mainly on conodonts, most of the Japanese radiolarian zones have been calibrated through correlation with zonal schemes established in other regions, and do not have a calibrated conodont biostratigraphy. Here we present the Upper Norian to Rhaetian $\delta^{13}C_{org}$ and radiolarian and conodont biostratigraphic records of the Upper Triassic bedded chert successions from the Mino belt, central Japan. Based on the stratigraphic distributions of marker species, five conodont zones are defined: the *Mockina bidentata*, *Parvigondolella andrusovi*, *Misikella hernsteini*, *M. posthernsteini* s.l., and *M. posthernsteini* s.s. zones (in stratigraphic order). *Misikella posthernsteini* s.l. is an intermediate species that underwent a morphological transition from *M. hernsteini* to *M. posthernsteini* s.s., and its stratigraphic distribution is revealed for the first time in the Panthalassic section. These conodont zones are comparable to the standard upper Norian and Rhaetian conodont zones of the western Tethys defined by Rigo et al. (2018). The Norian-Rhaetian boundary of the studied section has been placed at the last occurrence (LO) of the Norian radiolarian species *Betraccium deweveri*. Our study shows that the LO of *B. deweveri* coincides with the first occurrence (FO) of *M. posthernsteini* s.s., the index species of the NRB in the GSSP candidate section (Pignola-Abriola section in Italy). The FO of the Rhaetian radiolarian genera, such as *Palonaella, Pantanellium, Proparvicingula,* and *Fontinella*, coincide with the FO of *M. posthernsteini* s.s. in the study section, indicating that these radiolarian species are useful for identifying the NRB in the Panthalassic site. Furthermore, the $\delta^{13}C_{org}$ analysis showed a positive peak of ca. 1.5‰ above background values in the *M. posthernsteini* s.l. zone, followed by a negative trend, reaching the most negative peak (ca. 2‰) just before the first occurrence of *M. posthernsteini* s.s., and then returning to background. The $\delta^{13}C_{org}$ profile in the study section is consistent with contemporaneous $\delta^{13}C_{org}$ curves recorded in the Pignola-Abriola section (Rigo et al., 2024).

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Carbonate components of the Oxfordian (Late Jurassic) Friuli carbonate platform, as preserved in calciturbidites of the Belluno Basin

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Keywords: calciturbidites, Belluno Basin, Oxfordian.

During the Middle to Late Jurassic, the narrow pelagic Belluno Basin was part of a horst and graben submarine topography of the Adria passive margin (Picotti & Cobianchi, 2017). It was bordered to the east by the Friuli carbonate platform and by the Trento carbonate platform to the west. The Trento platform was already a pelagic plateau by the Middle Jurassic, while the productivity of the Friuli platform lasted until the Late Cretaceous. Nowadays the deposits of the Belluno Basin crop out in the eastern Southern Alps in Italy. Here we present the results of a detailed sedimentological, petrographical, geochemical and biostratigraphic analysis of a 115 m long stratigraphic section of the Belluno Basin located in the Tovena village area (Treviso), in the framework of the mapping campaigns for CARG geological map 084-Vittorio Veneto. This succession included numerous calciturbidites belonging to the Fonzaso Formation, which reflect the discharge of sediments from the Friuli platform into the basin. The succession was dated to the Oxfordian using nannofossil biostratigraphy on smear slides and SEM images. Petrographic analyses reveal distinct facies associations ranging from high-energy, platform-derived ooid-skeletal packstones of calciturbidites to low-energy, fine-grained mud-supported wackestones that represent the undisturbed deep-water sedimentation. The main skeletal components of calciturbidites are calcareous sponges and corals and numerous ooids are also present. This assemblage is comparable to coeval carbonate platforms in the Mediterranean area, but the abundance of ooids and their bimodal distribution in size and type (small and radial; large and micritic) are peculiar. Mean size and abundance of the ooids significantly increase from the Early-Middle Oxfordian to the Late Oxfordian (172,7 to 346,7 μm). We linked this trend to an enhancement in carbonate saturation state in the Western Tethys, as proposed by Trower et al. (2022) and Koeshidayatullah et al. (2022). This trend is further supported by a general positive trend of the $\delta^{13}C$-curve, which may suggest higher carbonate productivity on platforms towards the Late Oxfordian.

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Timing, mode and tempo of the major climatic transitions of the Early Pleistocene: a central Mediterranean perspective

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Keywords: Early Pleistocene, Central Mediterrranean, submillenial climatic fluctations.

The Early Pleistocene (ca. 2.588 – 0.774 Ma) marks a crucial turning point in recent climate evolution, as it represents the culmination of a 30 million years cooling process initiated by the definitive establishment of the Antarctic ice sheet. During this period, ice coverage intensified dramatically across the Northern Hemisphere, and a profound modification in both amplitude and duration of the glacial-interglacial (G-I) cycles progressively took place. Three major events can be identified within the interval of relevance. The first occurs at around 2.6 Ma, close to the Pliocene/Pleistocene boundary, when a triplet of severe glacial stages occurred (i.e., MIS 100, 98, 96) that are observed in sedimentary records globally (Lisiecki & Raymo, 2005). The second, between ca. 2.1 and 1.8 Ma, approximates the Gelasian/Calabrian boundary with the so-called "first deep glaciations" (Rohling et al., 2014). The third, also known as the "Early-Middle Pleistocene transition" (EMPT; approximately 1.2 - 0.6 Ma; Head & Gibbard, 2015), represents the latest thrust towards the modern G-I variability (shift from 40 kyr to ca. 100 kyr).

The Central Mediterranean region is acknowledged as the reference area for the Plio- Pleistocene stratigraphy, thanks to its exceptionally expanded open-marine sedimentary record, particularly well exposed in Southern Italy and Sicily, and its high sensitivity to both global and regional-local climatic changes. We attempted reconstructing a continuous, high-resolution benthic δ18O record throughout the Lower Pleistocene of Southern Italy, with a special focus on the three major climatic intervals mentioned above. Additional paleoclimatic proxies were investigated to corroborate our record and provide a robust and reliable chronological framework, including alkenones, planktic δ18O and calcareous nannofossils. Our findings contribute to improving our knowledge of the mechanism driving past climate changes, but also provides new insights into the short-term climate variability which we confirmed is a pervasive feature of the Early Pleistocene and may be of use for future climate forecasting.

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S20.

Mineral resources:
New routes for a secure and sustainable supply

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Study on heavy metals adsorption using spherical activated carbon (G-BAC)

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Keywords: activated carbon, heavy metals, adsorption.

This study investigates the adsorption performance of G-BAC, a spherical activated carbon produced by Kureha Corporation, for the removal of heavy metals including arsenic (As), thallium (Tl), selenium (Se), and antimony (Sb). G-BAC is manufactured from petroleum pitch through a binder-free synthesis with a highly uniform morphology and excellent mechanical stability.

Three replicates were prepared for each metal. Each replicate consisted of approximately 0.1 grams of G-BAC contacted with 0.5 mL of an aqueous solution containing the metal at an initial concentration of 700-800 ppm. The pH was adjusted close to neutrality. The samples were agitated mechanically at room temperature for 24 hours, then centrifuged to separate the solid and liquid phases. The solid residues were dried and analyzed using thermal analysis techniques (TG, DTG, DTA) and X-ray diffraction (XRD). At the same time, the liquid phase was examined by inductively coupled plasma mass spectrometry (ICP-MS).

Thermal analyses revealed alterations in the profiles of the post-adsorption samples, suggesting structural changes in the material due to metal interaction. Notably, DTG and DTA spectra exhibited slight but consistent shifts in thermal signals, indicating modifications in the decomposition behavior of surface functional groups.

XRD analysis revealed three characteristic peaks of the G-BAC structure (Wibawa et al., 2020) which were shifted in all metal-treated samples. In particular, the first peak moved to higher angles, indicating a reduction in interlayer spacing as calculated via Bragg's law. This shift was most pronounced in the arsenic-treated sample, implying a deeper or more invasive structural interaction.

Possible explanations for this phenomenon include: (i) the formation of bonds between heavy metals and oxygen-containing surface functional groups, leading to partial collapse of graphitic microstructures and/or (ii) the removal of interlayer species (e.g., water, oxygen), resulting in closer stacking of graphene layers (Fisher & Vreugdenhil, 2023).

ICP-MS analysis of the post-treatment solutions confirmed effective metal removal, except in the case of antimony, for which inconsistent results were probably due to its chemical instability in solution. The removal percentages indicate high adsorption efficiency, especially for arsenic.

These results emphasize the potential of G-BAC as an effective adsorbent for the removal of heavy metals from aqueous solutions and support further research on the structural modifications induced by adsorption processes.

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Constraining the timing of ore-forming processes in a late-Variscan greisen system from northern Sardinia, Italy

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Keywords: ore geology, mica dating, intrusion-related mineralisation.

In the Su Laccheddu area of northern Sardinia (Italy), a fluorine-rich, open hydrothermal system developed at the periphery of late-Variscan granites, forming Mo-W-F-LREE greisen and fluorite veins at the intrusive contacts with high-grade Variscan metamorphic rocks (Cossu et al., 2024). Magmatic relics include K-feldspar, plagioclase, zircon and monazite, whereas the greisen assemblage (~300-400°C; Pirajno, 2009) is dominated by muscovite and quartz. The progressive geochemical evolution of the system, marked by decreasing fluorine activity and temperature, led to the formation of sericite and chlorite, along with ore minerals such as molybdenite, scheelite, Bi-Te alloys, columbite, hematite, pyrite, synchysite-(Ce), and pyrochlore-(Y). The final hydrothermal stage was characterised by the deposition of fluorite and quartz veins, with minor barite and galena.

Electron microprobe analyses of white micas reveal a core-to-rim chemical zonation. Core composition is Si 3.08 apfu, Fe 0.06 apfu, Mg 0.01 apfu, Mn 0.003 apfu, Ti 0.002 apfu, Al 2.75 apfu, F 0.18 apfu, OH 1.82 apfu; rim composition is Si 3.13 apfu, Fe 0.15 apfu, Mg 0.02 apfu, Mn 0.007 apfu, Ti 0.005 apfu, Al 2.56 apfu, F 0.15 apfu, OH 1.84 apfu. The increase in Si, Fe, Mg, Mn, Ti, and the decrease in Al from cores to rims reflect a Tschermak-type substitution during greisenization, and the increase in OH and the decrease in F indicate progressively more hydrous and alkali-rich conditions, both consistent with the transition from magmatic to late-stage hydrothermal regimes.

Five samples were selected for *in-situ* Rb/Sr white mica geochronology using laser ablation–inductively coupled plasma mass spectrometry, with ages calculated with IsoplotR.

White mica Rb/Sr isochron ages from samples SLA2a, SLA3a, SLA5, and SLA6 yielded 270.5 ± 5.6 Ma, 278.6 ± 3.3 Ma, 285.6 ± 4 Ma, and 275 ± 6 Ma, respectively, showing no core-rim age variation. Sample SLA1, however, displayed isochron cores and rims dates of 292.6 ± 5.8 Ma and 277.3 ± 2.9 Ma, respectively.

The textural, chemical, and geochronological data indicate both prolonged and episodic fluid activity between ca. 293 and 270 Ma associated with the ore minerals genesis during the latest stages of the Variscan intrusion.

These findings provide a robust framework for future exploration in the Variscan basement, offering spatial, geochemical, and temporal constraints for granite-related ore deposits. They also contribute to refining genetic models of greisen-type mineralisation and enhancing predictive tools for similar metallogenic settings.

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The metallogenic database of Sardinia

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Keywords: ore deposits, critical raw materials, predictive modeling.

Sardinia is a historical mining region in Italy that was relevant in supplying raw materials to Europe during the 19th and 20th centuries. In line with the EU's commitment to sustainable development, driven by modern knowledge, technologies, and legislation, there is a growing need to map, evaluate and discover ore deposits.

A new metallogenic map of Sardinia is being developed as part of the Geosciences IR Project, coordinated by ISPRA. The mining and prospecting data from the mining activity period in Sardinia are being collected, filtered, and organised, then integrated with new information to create a robust, modern database of Sardinia's ore deposits. This will support ore modelling, economic assessments, metallogenic mapping, and future exploration planning.

The database includes the ore-defining parameters and technical information from mineralogy, lithostratigraphy, structural geology and mining operations. Sardinia hosts nearly 700 known mineral occurrences, many containing Critical Raw Materials (CRMs).

A large variety of ore deposit types reflect the complex geological evolution of Sardinia, associated to the different metallogenic events which succeeded from the Cambrian to the Holocene: i) Cambrian Pb-Zn-Fe-Cu MVT and SEDEX deposits; ii) Ordovician REE paleoplacers and oolitic Fe limestones; iii) Silurian stratabound Fe/pyrite deposits; iv) Variscan intrusion-related Pb-Zn-Cu sulphides porphyry, skarn and Ni-Co-Bi and Au-Ag veins; v) Late-Variscan Mo-W-Sn-REE greisens and feldspar-mica pegmatites; vi) Post-Variscan hydrothermal F-Ba-Pb veins; vii) Miocene epithermal HS and LS Au-Te, bentonite, kaolin, zeolite and Mn; viii) Pliocene volcanic-related perlite.

Sardinia exemplifies how former mining regions may still hold significant untapped potential due to past under-exploitation and under-exploration, according to modern economic requirements. Moreover, legacy mine data are essential for building predictive ore models, which can guide exploration in poorly explored areas and deeper geological settings. Advances in geological understanding over recent decades enable more accurate prediction, exploration, and modelling of mineral deposits, reinforcing Sardinia's strategic value in the context of Europe's raw material supply.

Detection of the petroleum and geothermal alterations by using remote sensing techniques: initial results of Alasehir (Manisa, Western Türkiye)

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Keywords: geological remote sensing, alteration mapping, geothermal analyse.

Starting from 1970s and still going on today, many researchers have used remote sensing methods to examine the evaluation and distribution of petroleum system. According to this purpose, technological improvements have control on the type of data being used. Today geological remote sensing applications are more commonly used. This study is aimed to examine the petroleum and geothermal potential of the Alasehir- Manisa region by using remote sensing techniques.

The Alasehir district is located within the Gediz Graben which features various hot springs and gas emissions, alteration zones and active hydrothermal system. Although no commercially viable petroleum has been found in the oil wells drilled in the study area in previous periods, the area is highly critical due to its potential for both geothermal and petroleum resources.

The research reveals that in surface rocks and soils, there are chemical differentiations related to hydrocarbon seepages, including: red beds bleaching, clay mineralization, secondary carbonate formations, secondary sulfide formations. These changes, including enrichment in ferrus iron, alterations in clay minerals and carbonates, and botanical anomalies can be detected through remote sensing methods by analyzing changes in their spectral properties (Saunders et al., 1999; Fu et al., 2007; Shirmard et al., 2020).

The study has two different main purposes. One is to identify and map the mineralogical alterations on surface which is caused by the hydrocarbon system. It is believed to provide more information about the petroleum system of the region. And second main purpose is to identify the geothermal potential of the area by using new remote sensing techniques.

Different types of optical imagery are used: Landsat and ASTER. Mineral index maps are generated from satellite multispectral remote sensing data. Spectral measurements are taken from the field and rock samples of these measurements are collected. A combination of both alteration mapping from multispectral remote sensing data and spectrometer analyses formed the working outline of this study. HR-1024 brand spectroradiometer is used for all spectral field measurements and also for the laboratory spectral measurements of the 124 collected samples. The XRD and petrographic analysis results of the field samples have been obtained. These results are correlated with the matching values of the samples' spectral signatures and are used in the verification of the analyses on mineral index maps. Laboratory studies of the spectral properties of rocks provide a connection between the mineralogy determined by the imagery, XRD and petrographic analyses.

The spectral measurements taken in the field are consistent with the measurements obtained from the samples in the laboratory. The result of this study indicates that remotely sensed data can detect possible areas of hydrocarbon induced mineralogic alterations. The initial results facilitated an approach to potential areas.

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Saunders D.F. et al. (1999) - Model for hydrocarbon microseepage and related near-surfac ealterations. AAPG Bull., 83, 170-185.

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The essential contribution of sedimentary petrology to understand sedimentary rocks-hosted ore deposits

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Keywords: carbonate diagenesis, ore minerals, hydrothermal fluids.

In ore geology, syngenetic deposits, formed at the same time as the enclosing rocks, are commonly distinguished from epigenetic deposits, in turn formed later than their host rocks. Sediment-hosted epigenetic deposits may range from those formed very early and at shallow burial depths to others formed much later, under a considerable burial, and possibly in a completely different geotectonic context compared to the one where host rocks were deposited. Diagenetic processes in carbonate sediments may operate before, during, and after ore mineral precipitation. These processes may change significantly the features of the original sediment and in particular porosity and permeability which influence the possibility of the rock to be crossed by a fluid flow and thus to become a mineral or hydrocarbon reservoir.

We present here data of a research carried out on Upper Triassic shallow platform limestones and dolostones (Bergamo Prealps, Lombardy) which host sphalerite, galena, fluorite and barite mineralizations which have been the object of historical extraction and modern exploration. We show that a multisciplinary study (stable isotope geochemistry, fluid inclusion microthermometry, radiometric dating) can provide useful data for interpreting ore formation, only if it is preceded by careful standard and cathodoluminescence petrographic analyses, aimed to infer the properties of the sediments/rocks at the time of mineralization.

Fluid inclusion microthermometry in sphalerite, fluorite and associated dolomite shows that precipitation temperatures were in the range of 70 to 140°C. However, some petrographic characteristics (e.g.: a dolomite-cemented ash layer with a minus-cement porosity of about 75%; micron-sized calcite and dolomite inclusions in quartz and sphalerite crystals; the high degree of mineralization of shale layers) document that ore minerals and the associated quartz and dolomite grew early in the diagenetic evolution, within a sediment which had not been significantly compacted i.e. deeply buried. Calcareous sediments which had already been locally cemented in a very early diagenetic stage, were not affected by replacement phenomena by e.g. dolomite and sphalerite confirming that permeability was a strong controlling factor on mineralization. A high permeability is not expected at considerable burial depths in fine-grained sediments which are known to suffer rapid porosity reduction by compaction during the earliest burial stages. This places a strong constraint on the time of mineralization, even more precise, albeit qualitative, than the direct radiometric dating of ore or gangue minerals, which often have wide error margins. Only with this approach can a chronology of events be reconstructed and correlated with tectonic and/or magmatic events, which in turn determine fluid composition and circulation. Furthermore, the risk of equating temperature with depth of ore formation, based solely on geothermal gradients, can be avoided.

Mineralogical and geochemical characterization of Barite from Acquappesa (Southern Italy): genesis, formation processes, and quantitative assessment

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Keywords: barite mineralization, multi-technique characterization, geo-mineralogical-heritage.

Barite is the naturally occurring form of barium sulfate ($BaSO_4$), widely used in various industrial applications, most notably as a weighting agent in drilling fluids for oil and gas wells (Aladesanmi et al., 2018). It is also extensively used in the manufacture of paints, rubber, plastics, glass, ceramics, pharmaceuticals, and radiological shielding materials (Johnson et al., 2017). The increasing global demand for barite highlights the importance of characterizing local mineral deposits from both industrial and scientific perspectives. This study focuses on barite occurrences at two sites within the municipality of Acquappesa (Calabria, Southern Italy), an area marked by significant geological heterogeneity and mineralogical diversity. A multi-technique analytical approach was employed to investigate the mineralogical, chemical, and microstructural characteristics of the barite samples. XRPD, TG/DSC and FTIR were used alongside advanced imaging and microanalytical techniques such as SEM, TEM, EPMA, and ICP-MS. These methods yielded comprehensive insights into crystal morphology, elemental composition, and genetic relationships with associated mineral phases. Field evidence from outcrops indicates that barite is commonly associated with Triassic phyllites and Lower Jurassic limestones, and also occurs as fracture fillings within the quartzites of the Cretaceous Frido Formation, in accordance with previously reported data in the literature (Dattola & Barone, 2024). The crystals are predominantly lenticular, although some specimens display tabular or lamellar habits, often occurring in association with calcite and iron oxides. Barite frequently forms rosette-like crystal aggregates. The results shed light on the genesis and variability of barite mineralizations in the Acquappesa area, contributing to a better understanding of the region's geo-mineralogical evolution. These mineral occurrences represent not only a potential industrial resource, but also a natural asset of scientific, didactic and aesthetic value.

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Dattola L. & Barone G. (2024) - Minerali della Calabria. Gruppo Mineralogico Lombardo, Associazione Italiana di Mineralogia, 256 pp.

Johnson C.A. et al. (2017) - Barite (Barium). U.S. Geological Survey, Professional Paper 1802 (D), D1-D18, https://doi.org/10.3133/pp1802D.

Genetic features of North Gondwana vanadium-bearing Silurian black shales: the South East Sardinia (Italy) case

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Keywords: vanadium, black shales, Sardinia.

Vanadium represents a critical metal for the global economy, due to its increasing application in low CO_2-emission technologies, such as vanadium redox flow batteries. Black shale-hosted V-deposits cover about 80% of the potential global V resources, although only < 2% of them are currently considered economic.

During Silurian, significant black shale Graptolites-hosting successions, which contain variable amounts of vanadium and other metals, were deposited under strong anoxic conditions in the North Gondwana realm, from Northern Africa to Southern Europe and Middle East. South East Sardinia (Gerrei Tectonic Unit; Carmignani et al., 1994) is one of the areas where these successions have been encountered, and made object of preliminary investigation.In our research (Boni et al., 2025), we carried out combined geochemical and mineralogical analyses in order to determine major and trace elements concentration in the Silurian black shales of Sardinia together with metal deportment in specific mineral phases. We then compared the obtained results with published data on Silurian black shales occurring in other globally significant sedimentary basins.

Sardinian black shales have variable V amounts, ranging from hundreds to thousands ppm and organic carbon contents up to 10.1 wt%. These values, together with observed Th/U, Ni/Co and V/Cr ratios, demonstrate that the initial sedimentary environment was clearly anoxic. The positive correlation between V and total organic carbon indicates that organic matter has retained most of vanadium. Rutile can contain significant V amounts, where vanadium is substituting for Ti, as reported in several low-to-moderately metamorphosed black shale deposits around the world. Vanadium-bearing illite, with a V_2O_3 content ranging between 0.63 and 2.97 wt%, was detected locally. In this mineral V(III) readily substitutes for aluminum in the octahedral sites of clays, and clay recrystallization or authigenesis would include V(III) in the forming clay. Local V concentrations in rutile and illite in SE Sardinia may derive from metal remobilization during diagenesis and low-grade (Variscan) metamorphism. The association of V-bearing illite and V-rutile has been quoted by several authors dealing with V-enriched black shales in the Baltic realm. However, mineral phases with V as a major component (e.g., roscoelite, mannardite), reported from other shale-hosted V deposits, have not been identified in SE Sardinia so far.

Compared to other coeval Silurian successions of North Gondwana, Sardinian black shales have also anomalous values of Sb, Ba, Se, Mo, As, Mo, F and U, this suggesting that, in the frame of a peculiar sedimentary process that occurred in a similar way at the global scale, distinct controls existed in the different basins.

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PGE enrichments in supra-Moho chromitites: insights from texture and chemistry at the nanoscale

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Keywords: PGM, Pt-Fe alloy, ophiolite.

Platinum Group Elements are six metals (Ru, Rh, Pd, Os, Ir and Pt) grouped together for their similar chemical and physical properties and frequent co-occurrence in mineral deposits. However, they show distinct geochemical behaviours: PPGE (Pt, Pd, Rh) are less refractory and tend to partition into the melts generated in the upper mantle, whereas IPGE (Ru, Os, Ir) are more refractory and remain in the residual mantle. Most ophiolitic chromitites worldwide are relatively enriched in IPGE, reflecting depleted mantle sources. PPGE-enriched chromitites have been however detected in some deposits worldwide, where PPGE minerals are either alteration phases (more common) or primary phases (rare occurrence).

A rare occurrence of Pt-rich supra-Moho chromitites from Tropoje (Albania) has been studied through advanced electron microscopy and spectroscopy techniques, focusing on composite PGM grains. The examined grains consist of a large Pt-Fe alloy (> 15 μm), a $(Ru,Os,Ir)S_2$ phase (< 5 μm), and a Pd-Rh-As alloy (< 5 μm). Micro- and nanoscale investigations uncover distinctive textural features, most notably the presence of Rh-Ru-rich inclusions within the Pt-Fe alloy. These inclusions appear as both nanoscale clusters (tens of nm) and larger dendrites (tens of mm), with an average composition of $Rh_{0.8}Ru_{0.2}$ hosted in a Pt_3Fe matrix. TEM images exhibit diffraction contrast associated with strain fields, which are attributed to the presence of nanoscale inclusions and crystallographic defects within the Pt_3Fe structure. High-resolution TEM (HRTEM) at the interface between the $Rh_{0.8}Ru_{0.2}$ inclusions and the Pt_3Fe matrix shows perfect crystallographic alignment, indicating coherent interfaces and a structurally integrated relationship between inclusions and host alloy.

The coexistence of Pt_3Fe, $(Ru,Os,Ir)S_2$ and Pd-Rh-As may suggest an original high-temperature single-phase alloy. Upon cooling, $(Ru,Os,Ir)S_2$ and Pd-Rh-As nucleated independently, while some Ru and Rh remained trapped in the Pt_3Fe, likely resulting in a supersaturated solid solution (i.e., a metastable structure containing Rh and Ru above equilibrium solubility in the Pt-Fe alloy). Further cooling led to fine-scale Rh-Ru precipitation, in crystallographic alignment with the Pt-Fe matrix. The rare presence of laurite may imply either an initial limited S availability or an early nucleation of metallic Ru-Os clusters at high-T, later reacting with S as temperature dropped, leading to a slight fS_2 increase. Crustal-level chromitites may have formed from late pulses of evolved, Pt-rich melts under reducing and S-poor conditions, promoting the formation PPGE-rich phases. Upon cooling composite grains formed whose texture and composition reflect the different behaviour of PGE: Ru, Os and Ir bond with S, Pd bonds with As and Pt bonds with Fe. Rh remains mostly in the Pt-Fe alloy until it exsolves as nano-inclusions at lower temperature when its diffusivity is too low to allow the formation of larger crystals.

Geochronology of mineral deposits: what for and how?

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Keywords: mineral deposits, U-Pb geochronology.

The study of mineral deposits is a multidisciplinary, object-oriented science that integrates data from a wide array of tools and methods. Among these, geochronology plays a crucial role in constraining the timing and duration of geological processes. Owing to their geochemical twinship and well-characterized decay schemes, the U-Pb systems (^{238}U to ^{206}Pb and ^{235}U to ^{207}Pb) are the most widely used geochronometers for investigating deep-time processes (> 1 Ma). The expanding variety of datable minerals now enables U-Pb dating across nearly all types of mineral deposits, from supergene to magmatic and metamorphic origins.

Despite this versatility, the design of a U-Pb geochronological study remains highly dependent on the study's objectives, comprehensive field and petrographic documentation, the availability and suitability of datable minerals in relevant paragenetic stages, and practical constraints such as cost and laboratory access.

In mineral deposit research, U-Pb dating is most commonly applied to constrain the timing of ore-forming processes and associated magmatic, sedimentary, metamorphic, or hydrothermal events. Such temporal constraints contribute to placing these processes within a broader geodynamic context and help identify the triggers of mineralization. Beyond age determination, U-Pb geochronology can also inform the duration and rates of key ore-forming processes, providing a framework for calibrating models and testing long-standing hypotheses. For instance, high-precision geochronology has shown that porphyry copper deposit size correlates with the duration of ore formation—ranging from tens of thousands of years for ~3 Mt Cu deposits to several million years for giant deposits containing ~100 Mt Cu (Virmond et al., 2024). A comparable relationship has also been envisioned for MVT deposits (Tavazzani et al., 2024)

However, the power of U-Pb geochronology comes with technical challenges. These include handling common Pb-bearing and Pb-leaking minerals, managing both internal and external uncertainties, selecting appropriate reference materials, and navigating various data reduction protocols and lab practices. The rise of high-precision techniques and interlaboratory calibration efforts has highlighted discrepancies with less precise but widely used in-situ methods such as LA-ICP-MS and SIMS/SHRIMP that should be carefully accouted for before any geological interpretation (Chelle-Michou & Schaltegger, 2023). These considerations underscore the importance of thoughtful study design and awareness of the (often unstated) assumptions and limitations inherent in U-Pb geochronology.

Chelle-Michou C. & Schaltegger U. (2023) - U–Pb Dating of Mineral Deposits: From Age Constraints to Ore-Forming Processes. In: Huston D., Gutzmer J. (Eds), Isotopes in Economic Geology, Metallogenesis and Exploration. Mineral Resource Reviews. Springer, Cham, 37-87, https://doi.org/10.1007/978-3-031-27897-6_3.

Tavazzani L. et al. (2024) - Not so fast: Million-years of metal precipitation in Mississippi Valley type deposits inferred from in-situ petrochronology of hydrothermal carbonates. Earth Planet. Sc. Lett., 636, 118718, https://doi.org/10.1016/j.epsl.2024.118718.

Virmond AL. et al. (2024) - Multi-million-year magmatic and hydrothermal activity is key to the formation of supergiant to behemothian porphyry copper deposits. Contrib. Mineral. Petr., 179, 88, https://doi.org/10.1007/s00410-024-02167-4.

Critical raw materials in the Parma and Piacenza provinces (Northern Apennines Front – Po Basin Foredeep): a preliminary assessment of their occurrence and distribution in the fluids

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Keywords: CRM, fluids, Northern Appenines.

The energy transition is a critically important issue in today's global context. More and more countries are working towards a sustainable and energy-efficient future (De Vincenzo, 2022). This shift also drives the search for essential minerals and elements for the storage, distribution, and supply of energy generated from these new sources. An increase in demand is expected for elements such as boron, barium, lithium, magnesium, and strontium. They are essential to achieve the energy transition (Hofmann et al., 2018), but for countries such as Europe, these elements are defined as Critical Raw Materials (CRM) (EU, 2024); because their availability within European borders remains limited. Nonetheless, recently, Dini et al. (2022) proposed a first map of lithium resources in Italy, focused on extracting CRMs from unconventional deposits such as geothermal waters, and formation brines. Despite the identification of possible extraction bands of CRMs in the Italian territory, there are still several gaps that limit their extraction, including: i) lack of regional maps and details of distribution/concentration of CRMs; ii) limited analyses of the lithological units influencing the composition of waters containing CRMs; iii) lack of knowledge about the control of the main tectonic structures on the distribution/concentration of the fluid leakage zones containing CRMs; and iv) inconsistency between older and more recent chemical analyses. In this study, we have tried to solve the gaps and limitations described above, at least for the formation fluids (brackish to brine waters) in the provinces of Parma and Piacenza, focusing on the Northern Apennine front and adjacent Po basin foredeep.

To understand the origin, distribution, and migration paths of these fluids, a range of data types and investigation methodologies have been combined, including geological data and geochemical analyses. The data were first inserted in a GIS-based (QGis) database, then used to create new distribution maps for the CRMs (indicated previously), and finally enclosed in a new three-dimensional geological model built with Leapfrog Geo (Seequent TM). The latter allowed for a faster and simplified understanding of CRM-bearing waters' migration and outflow zones. Preliminary results indicate that the waters richest in CRMs are mainly contained in and sourced from the Middle Miocene sandstone-rich unit. In this framework, tectonic structures (mainly fault-related folds), stratigraphic discontinuities, lithological heterogeneities, and impermeable units generate at least three scenarios of water migration and occurrence in the investigated area. In particular, our findings show that the waters having higher availability for the extraction of CRM are Br- and I-rich brines in Salsomaggiore Terme and Monticelli Terme.

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Hofmann M. et al. (2018) - Critical raw materials: A perspective from the materials science community. Sustain. Mater. Techno., 17, e00074, https://doi.org/10.1016/j.susmat.2018.e00074.

Hyperspectral characterization of U-V deposits in the La Sal district, Paradox Basin, USA

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Keywords: U-V deposits, hyperspectral analysis, La Sal district.

In this study, we present a comprehensive hyperspectral characterization of uranium and vanadium deposits in the La Sal district, located on the border between Utah and Colorado, USA. The objective is to enhance exploration strategies by identifying target absorption features related to alteration assemblages associated with U-V mineralization.

Mineralization primarily occurs within the bleached zones of the Salt Wash Member of the Jurassic Morrison Formation, which comprises subarkosic sandstones and mudstones, composed mainly of clay minerals, micas, and quartz, with trace amounts of feldspar and organic compounds. The U-V ore assemblage consists of montroseite, uraninite, and coffinite, formed during diagenetic processes, such as quartz overgrowths. Vanadium was also found in phyllosilicates, a consequence of the back-reaction of montroseite with quartz and other minerals (Barton & Barton, 2024; Bos Orent et al., 2024).

Hyperspectral imaging was conducted on hand samples collected from the La Sal district. The data processing was performed by applying band ratios and indices based on the diagnostic spectral features of the bonds and related minerals involved (Laukamp et al., 2021). The hyperspectral analysis enabled the detection of illite with variable crystallinity, chlorite, kaolinite, calcite, and supergene phases such as Fe-oxide/hydroxide and jarosite. Shifts in absorption features suggest compositional variations: (1) illite shows a shift in wavelength from 2204 nm (Al-rich) to 2215 nm (Al-poor), potentially indicating substitution of Al by V3+ in the octahedral site; (2) chlorite absorption shifts from 2243 nm to 2249 nm according to the Fe content. Additional features observed at around 1750 nm and 1783 nm may reflect the presence of sulfates, plant residues, or hydrocarbons. VNIR spectra allow the identification of electronic transitions associated with transition metal ions (Rossman, 2014).

The identification of diagnostic spectral signatures related to V-bearing phases is particularly promising for future applications in satellite-based remote sensing, enabling broader-scale and cost-effective exploration in similar geological settings.

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Bos Orent E. et al. (2024) - Characterization of U(-V) deposits in the La Sal district, UT and CO and their relationship to paradox basin fluid flow. Min. Metall. Explor., 41, 2693-2721, https://doi.org/10.1007/s42461-024-01062-7.

Laukamp C. et al. (2021) - Mineral physicochemistry underlying feature-based extraction of mineral abundance and composition from shortwave, mid and thermal infrared reflectance spectra. Minerals, 11, 347, https://doi.org/10.3390/min11040347.

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Application of satellite and proximal hyperspectral sensing to target Li mineralization in volcano-sedimentary deposits: The McDermitt caldera (USA) case study

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Keywords: lithium, McDermitt caldera, hyperspectral analysis.

This study provides satellite and proximal hyperspectral analysis of lithium (Li)-bearing volcano-sedimentary environments aimed at determining the target absorption features of alteration assemblages to be used as exploration vectors towards analogous Li-mineralized systems. The approach was applied to the McDermitt caldera (USA), where Li mineralization occurs in the form of clay minerals forming from the alteration of glass-rich extrusive igneous rocks in endorheic lacustrine basins (Putzolu et al., 2025).

The surface-exposed areas of the caldera were investigated using hyperspectral imagery from the German Environmental Mapping and Analysis Program (EnMAP). Satellite data were validated by analyzing samples from the Jindalee McDermitt Li deposit, using hyperspectral imaging with Headwall Photonics cameras. Complementary mineralogical and geochemical analyses were also conducted on the same samples to further support spectral interpretations.

The creation of hyperspectral feature distribution maps was achieved using band ratio analysis and minimum wavelength techniques, implemented in ENVI 5.6 and the open-source Python package "hylite" (Laukamp et al., 2021; Thiele et al., 2021). This methodology enabled the detection of various minerals, including amorphous silica, Fe-smectite, Mg(Li)-smectite (hectorite), calcite, and zeolites.

The samples, which predominantly contain a Mg(Li)-smectite + amorphous silica assemblage, show distinct absorption features at 2200 nm and 2306 nm, detectable within the EnMAP spectral range. Analysis of the corresponding hyperspectral feature distribution maps and the comparison with ground control samples, compared with ground data, confirmed that the 2200 nm and 2306 nm absorption features can be effectively used as mineralogical-hyperspectral vectors for identifying Li-prospective areas on a caldera-scale. This spectral footprint was applied to the High Rock Caldera Complex, a similar system without Li mineralization (Coble & Mahood, 2016). The analysis revealed the absence of the characteristic 2200+2306 nm feature, indicating that these spectral features could be used to target lacustrine sequences with mineralogical characteristics similar to those found in Li-mineralized deposits.

Coble M.A. & Mahood G.A. (2016) - Geology of the High Rock caldera complex, northwest Nevada, and implications for intense rhyolitic volcanism associated with flood basalt magmatism and the initiation of the Snake River Plain-Yellowstone trend. Geosphere, 12, 58-113, http://doi.org/10.1130/GES01162.1.

Laukamp C. et al. (2021) - Mineral physicochemistry underlying feature-based extraction of mineral abundance and composition from shortwave, mid and thermal infrared reflectance spectra. Minerals, 11, 347, https://doi.org/10.3390/min11040347.

Putzolu F. et al. (2025) - Volcano-sedimentary deposits: overview of an emerging type of Lithium resource. Econ. Geol., 120(3), 541-573, https://doi.org/10.5382/econgeo.5135.

Thiele S.T. et al. (2021) - Multi-scale, multi-sensor data integration for automated 3-D geological mapping. Ore Geol. Rev., 136, 104252, https://doi.org/10.1016/j.oregeorev.2021.104252.

MADAM - Mobility And distribution of critical raw materials through the crust: a micro-tectonic perspective (Fondazione Cariplo, grant n°2024-0348)

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Keywords: continental crust, melt-transfer shear zone, multidisciplinary approach.

Raw Materials are essential to the world's economy and everyday life. In particular, the "Critical Raw Materials" (CRMs) are a group of elements and minerals crucial to produce various high-tech products, medical devices, industrial and energetic applications. Since the exponentially increasing demand for the CRMs in the recent times, geology plays an essential role in the study of the geological processes, which brought to the genesis, mobility and distribution of the CRMs and is therefore crucial for finding new strategies within the system of a circular economy and welfare (European Commission, 2023). Project MADAM aims at investigating the processes leading to CRMs concentration across potential melt-transfer zones with the final purpose to improve our knowledge on CRMs mobility, localization and distribution. I choose to use as case study the Ivrea-Verbano Zone (IVZ, Provincia del Verbano-Cusio-Ossola) as it is one of the best-preserved lower crustal sections in the world characterized by (ultra)mafic and metasedimentary rocks. Recently, several authors (Locmelis et al., 2021 and reference therein) reprised the ore characterization in terms of processes promoting CRMs metal mobility and distribution across the lower crust-upper mantle boundary. However, modern knowledge on the mineral potential of large sectors of the IVZ is still scarce. Three specific crustal sectors and localities from the IVZ lower crust are selected for this project: i.e., Campello Monti in Val Strona di Omegna, Anzola in Val d'Ossola and Finero in Val Cannobina. These zones have been already described as potential melt-transfer zones (Daczko & Piazolo, 2022) wheremineralization enriched in Co, Ni, Ti, Cu, Li and PGE critical elements occur (i.e., sulphurs, chromites, pegmatites, carbonatites). Since the complexity in identifying the melt-transfer zones, the project will focus on microscale studies to investigate the physical-chemical conditions and mechanisms of fluid/melt interactions potentially leading to metal mobilization and concentration to macroscale. In particular, the project plan is to adopt a multidisciplinary approach with the aim to collect in different field campaigns several samples from outcrops where CRMs-mineralizations have been documented. Combining field-based observations with detailed petro-chemical and microstructural studies (i.e., SEM, EBSD, XRF, LA-ICP-MS), numerical modelling and 3D tomography of CRM-bearing samples, we expect to quantify and characterize, for the first time, the melt-rock interaction processes leading to the mobilization and accumulation of the critical materials. These activities will provide detailed information for both the petro-structural evolution of deep melt-transfer zones (to be reproduced in experimental petrology labs) and their role as paths of metal migration, recycling and concentration at various crustal levels.

Daczko N.R. & Piazolo S. (2022) - Recognition of melferite–A rock formed in syn-deformational high-strain melt-transfer zones through sub-solidus rocks: A review and synthesis of microstructural criteria. Lithos, 106850.

European Commission (2023) - Study on the critical raw materials for the EU 2023. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Grohol, M. and Veeh, C. Final report, Publications Office of the European Union.

Locmelis M. et al. (2021) - On the formation of magmatic sulphide systems in the lower crust by long-lived mass transfer through the lithosphere: Insights from the Valmaggia pipe, Ivrea Verbano Zone, Italy. Terra Nova, 33(2), 137-149.

Formation mechanisms of the Perda Niedda Fe-Sn-F-Zn skarn mineralization (SW Sardinia): insights from garnet and magnetite Sn contents

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Keywords: CRM, raw materials, resources.

The Perda Niedda Fe-F-Sn-Zn skarn (Domusnovas, SW Sardinia) is set on Cambrian metacarbonates, along the contact with hematite-rich Ordovician metaconglomerates and Early Permian (289 Ma), ilmenite-series leucogranites of the Oridda pluton. The mineralized portion of the skarn is known for 30000 m^3 and a depth of 30 m, consisting of abundant magnetite, fluorite and sphalerite lenses mined from late 1860s to late 1990s. The paragenetic sequence includes: 1. a prograde assemblage of garnet, with a light green core and a darker rim zoning with magnetite inclusions; 2. a retrograde/sulfide assemblage of amphibole, chlorite, phlogopite, talc, with abundant magnetite, fluorite, cassiterite and pyrite and subordinate sphalerite, chalcopyrite, löllingite, arsenopyrite, pyrrhotite, marcasite and galena. Massive quartz veins with minor cassiterite crop out near the granite and evolve into alternating bands of magnetite-cassiterite-sphalerite and fluorite-quartz-chlorite along the skarn.

The composition of garnet, magnetite, sphalerite and arsenopyrite was investigated with SEM-EDS, EPMA and LA-ICP-MS analyses. Garnet (avg $Adr_{96.9}Grs_{3.1}$ composition) features weak W (avg 114 ppm) and In (avg 44 ppm) enrichments and a maked Sn zoning from core (2000-9956 ppm) to rim (up to 6 wt%). Magnetite is high in Si (avg 6600 ppm, max 2.44 wt%), Al (avg 500 ppm, max 3000 ppm) and Mg (avg 500 ppm, max 1700 ppm); trace elemental contents of Sn (avg 894 ppm, max 6528 ppm), W (avg 8 ppm, max 169 ppm), Ge (avg 29 ppm, max 173 ppm) are above average of most Fe-skarns (Dare et al., 2014). Prograde magnetite enclosed in garnet rims is Sn-rich (1000-4000 ppm), while magnetite from retrograde facies has low Sn contents (bdl-500 ppm) and cassiterite µm-scale inclusions. Sphalerite is enriched in Fe (avg 8.37 wt%), In (avg 2600 ppm) and Bi (avg 1300 ppm). The arsenopyrite geothermometer provided temperatures of 450-470°C for the retrograde/sulfide stage.

The first prograde growth of garnet and magnetite was mostly controlled by exchange reactions between metacarbonates and hematite-rich conglomerates, which contributed significantly to the Fe intake of the system. The Sn input was generated by magmatic fluids around the peak of temperature (> 550 °C), forming Sn-rich garnet rims and its magnetite inclusions; during this stage, garnet acts as a Sn reservoir. The following input of lower temperature (450-370°C) and HF-rich fluids caused hydrothermal alteration of garnet and amphibole, chlorite, phlogopite and talc formation. This results in Sn remobilization and reprecipitation as cassiterite grains and inclusions in magnetite, together with fluorite, Fe-sphalerite (likely with Bi-sulfosalts inclusions) and low-sulfidation Fe-arsenides (löllingite) and -sulfides (arsenopyrite, pyrrhotite, marcasite). The late stage evolution of the fluid coincides with less reducing and higher sulfidation conditions, causing abundant precipitation of pyrite.

Dare S.A.S. et al. (2014) - Trace elements in magnetite as petrogenetic indicators. Miner. Deposita, 49, 785-796, https://doi.org/10.1007/s00126-014-0529-0.

The feldspar oxymoron - abundant yet critical - and the underlying geological and technological factors

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Keywords: albitite, ceramic, critical raw material.

Despite its widespread and abundant presence in the Earth's crust, feldspar has proven to be critical for the European Union. This importance stems from two converging factors: the strong demand for sodic feldspar in ceramic tile production, averaging 5.8 million tons per year since 2020, and the existence of vast albitite deposits in southwestern Turkey, where output has peaked at 16 million tons per year and where most global reserves are concentrated. The demand for other fluxes (potassic feldspar, mixed Na-K quartz-feldspathic rocks, nepheline syenite, etc.) is fully satisfied by European deposits, which have averaged 4.4 million tons per year since 2020. To comprehend the reasons behind this apparent contradiction, two pertinent questions must be addressed: Why is sodic feldspar so crucial in ceramic tile technology? And why are economically exploitable albitite deposits so scarce? The role of feldspathic fluxes during firing is re-examined within a new framework (glass formation boundary, vitrification path, enabler or auxiliary flux) to elucidate the peculiar technological behaviour of sodic feldspar. A brief overview of the occurrence, genesis, and compositional characteristics of albitite deposits is provided, emphasizing the geological aspects pertinent to the ceramic tile industry. This type of albitite is primarily found throughout the Mediterranean region, extending to the westernmost parts of India and the Nubian Shield in Egypt. Outside of these areas, albitite ores of ceramic interest are exceedingly rare. This highlights the necessity for a genetic model of albitite deposits. The discussion will highlight the challenge of mitigating these critical issues, while also addressing future research directions in both the geological and ceramic fields.

Tracing the origins of Vallarsa's gold: new analytical perspectives on an unexpected finding

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Keywords: gold mineralization, VVP, Vallarsa.

In 1996, during a routine field survey, a collaborator of the Civic Museum of Rovereto (Trento, Northeastern Italy) recovered a small fragment of native gold-bearing mineralization from the alluvial sediments of the Leno creek in the Vallarsa valley. This discovery, though modest in scale, sparked renewed interest in a region traditionally considered geologically unsuitable for gold mineralization. Despite longstanding local legends, sporadic press reports, technical reports (Moretti, 1927) and historical notes alluding to the "Gold of Vallarsa," no previous scientific documentation had ever confirmed the presence of native gold in the area. Previous geological and mineral exploration campaigns had conclusively attributed known mineral occurrences in Vallarsa and adjacent areas to non-auriferous systems.

This study presents a detailed petrographic, mineralogical, and lead (Pb) isotopic characterization of the gold-bearing sample, placing it within the broader geodynamic and metallogenic framework of the region. The fragment was found to consist of quartz and sulfide phases associated with native gold, suggesting a hydrothermal origin. The evidence points toward a low-sulfidation epithermal system, potentially linked to shallow fluid circulation processes associated with Tertiary magmatism of the Veneto Volcanic Province (VVP). Although the Pb isotopic signature of the gold does not fully coincide with that of known VVP magmatic rocks, it remains consistent with a VVP-related hydrothermal system and does not support derivation from Alpine sulfide deposits in the central-eastern Alps (Nimis et al., 2012; Brombin et al., 2021).

Comparative isotopic analysis of a marcasite sample from Val Gerlano reveals a distinct composition from that of the gold-bearing fragment, yet does not exclude a shared metallogenic environment. In contrast, isotopic data effectively rule out any genetic relationship between the Vallarsa gold and the sulfide mineralizations of the nearby Recoaro area (Val Mara), reinforcing the hypothesis of a localized, possibly previously unrecognized, hydrothermal system.

Beyond offering a rigorous analytical profile of the specimen currently preserved at the Civic Museum of Rovereto (Inventory No. E 00015), this work provides the first robust scientific framework for assessing the plausibility of native gold mineralization in the Vallarsa valley. It also reopens the discussion on historical narratives and undocumented field observations, now supported by analytical evidence. These results may serve as a reference point for future investigations into gold mineralization in Vallarsa, the Veneto Volcanic Province basin, and associated fluvial deposits.

Brombin V. et al. (2021) - New geochemical and geochronological data on the Cenozoic Veneto Volcanic Province: Geodynamic inferences. Lithos, 406-407, 106507.

Moretti E. (1927) - L'oro nella regione a nord del Pasubio? La Miniera Italiana XI, 5, 308.

Nimis P. et al. (2012) - Lead isotope systematics in hydrothermal sulphide deposits from the central-eastern Southalpine (northern Italy). Eur. J. Mineral., 24, 23-37.

Crystallization of hausmannite and romanechite within the red encrustations covering limestone substrate in the Apulian karst landscape of Southern Italy

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Keywords: red encrustations, hausmannite, romanechite.

The multidisciplinary approach combining scanning electron microscopy (SEM) with energy-dispersive (ED) spectrometer, Micro-Raman spectroscopy, wavelength dispersive X-ray fluorescence (WD-XRF) spectroscopy, and powder X-ray diffraction (XRD) methods allows for the detection of mineralization associated with specific paleoenvironmental conditions in the study of alteration products (red encrustations and calcite nodules) on karst limestone substrates.

Samples of nodules and red encrustations within a small paleo-doline in the Apulian karst on Mesozoic carbonate successions, contain Mn and/or Mn-Ba phases (Micheletti et al., 2023), which have been investigated in detail.

Hausmannite (Mn_3O_4, where Mn exhibits mixed valence states of 2+ and 3+) forms within fractures and pockets with euhedral habitus when Mn^{2+} reaching supersaturated conditions under oxidizing conditions, was partially converted to Mn^{3+} (Tholkappiyan et al., 2018). Subsequently, the availability of Ba^{2+} in the circulating solutions facilitates the formation of romanechite ($Ba_2Mn_5O_{10}\cdot xH_2O$, where Mn is present in both 3+ and 4+ valence states) around the hausmannite testifying even more oxidizing conditions.

The structural characteristics of romanechite, which adopts concentric and rhythmic globular shapes around and within clay minerals, attest its relationships with mud deposits (Fornelli et al., 2024). On the other hand, the presence of Kaolinite (it makes up about 60% of the insoluble residue of carbonate encrustations) along with detrital quartz granules, plagioclase and K-feldspars suggest that these phases are fundamental constituents of the mud. According to experimental paper of Yang et al. (2023), clay minerals play a crucial role in the formation of Mn-oxides/hydroxides. They capture divalent cations such as Fe^{2+}, Mg^{2+}, Mn^{2+}, and Ba^{2+} stabilizing the octahedral layers and promoting the growth of phyllosilicate structures, such as Kaolinite, which incorporates Mn and Mn-Ba oxides/hydroxides on its surface.

The genetic process responsible for the growth of hausmannite and romanechite can be described as follows: the limestone substrate interacts with stormwater runoff enriched in siliciclastic mud and CO_2, these muddy waters settle on the carbonate surface, leading to the dissolution of $CaCO_3$. Under these conditions, Mn^{2+}, Fe^{2+}, and Ba^{2+} derived from the mud and/or limestone dissolution are present in circulating solutions that penetrate the fractures of the karst limestone. Probably, subsequent evaporation of water with related temperature rise leads to oxidizing conditions with release of CO_2 and the re-precipitation of calcite, crystallization of hausmannite, and, ultimately, formation of romanechite.

Fornelli A. et al. (2024) - First Record of Romanechite in the Apulian Karst (Southern Italy) resulting from the interaction of limestones and clay minerals. Minerals, 14, 935, https://doi.org/10.3390/min14090935.

Micheletti F. et al. (2023) - Petrographic and Geochemical Inferences for Genesis of Terra Rossa: A Case Study from the Apulia n Karst (Southern Italy). Minerals, 13, 499, https://doi.org/10.3390/min13040499.

Tholkappiyan R. et al. (2018) - Investigation on the electrochemical performance of hausmannite Mn_3O_4 nanoparticles by ultrasonic irradiation assisted co-precipitation method for supercapacitor electrodes. J. Taibah Univ. Sci., 12(5), 669-677, https://doi.org/10.1080/16583655.2018.1497440.

Yang Y. et al. (2023) - Surface-induced oxidation of Mn (II) and crystallization of manganese (hydr) oxides on clay minerals. Geochim. Cosmochim. Acta, 363, 129-146.

The antimony (Sb) resource in southern Tuscany: textural and geochemical characterization with 3D reconstruction of an orebody (Montauto mining area)

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Keywords: historical mining activity, antimony mineralization, 3D geological modelling.

Europe is strongly dependent on foreign suppliers for several critical raw materials (CRMs), with limited mining production. Antimony (Sb) was added in the Europe CRMs already from the first list in 2011, finding large uses in strategic sectors. To support the constantly increasing demand, new Sb orebodies are to be discovered, explored and exploited within EU, to diversify the supplies and minimize geopolitical risks, together with the possibility to recover Sb also from secondary sources (i.e., historical mining wastes).

In this scenario, Italy has recently adopted the EU CRMs Act, promoting a national exploration plan. Antimony has been historically extracted in Tuscany and Sardinia, leaving a heritage of geological data (e.g., mining reports, lithological/geochemical drill logs) and mineral wastes. These Sb districts represent an exceptional case study for the assessment of potential Sb resources and associated CRMs in Italy. Available geological data on the southern Tuscany Sb district are dated (e.g., Lattanzi, 1999), and the geometries, volumes, and associated CRMs contents of the mineralized bodies are still largely unknown.

Here we present the first results of the PhD project that aims to provide: (i) a geological survey of Sb resources in Tuscany with implications on ore genesis and exploration, (ii) textural, mineralogical and geochemical investigations on Sb ores, and (iii) a 3D geological model of the selected orebodies (and potentially unexploited bodies) with probabilistic functions to conduct uncertainty analysis.

Field surveys and sample collection were conducted in several areas of the Tuscan Sb district (Mancianese area; e.g. Montauto, Tafone, Pozza al Lino and Poggio Fuoco areas) integrated by textural (reflected light microscope, SEM) and mineral chemistry (EPMA and LA-ICP-MS analysis) investigations.

The data are used for 3D reconstruction of the Montauto orebody with Gempy, an open-source Python-based software (Jüstel et al., 2023). The 3D modelling represents, in the exploration plan, a crucial tool to optimize the project planning and the evaluation of the potential available resources. In addition, applying uncertainty calculation functions it is possible to develop a more robust and reliable geologic model. The planned activities will contribute to the evaluation of Italian Sb mining potential, which is almost unknown today (SCRREEN, 2023), as well as to that of possible associated CRMs. The knowledge of this information is crucial for the characterization of the mineral resource and for the formulation of genetic models that can also be applied in other geological settings with similar ore characteristics across Europe.

Jüstel A. et al. (2023) - From Maps to Models-Tutorials for structural geological modeling using GemPy and GemGIS. J. Open Source Educ., 6(66), 185.

Lattanzi P. (1999) - Depositi epitermali di metalli preziosi in Italia: una panoramica. Mineral. Deposita, 34, 630-638.

SCRREEN (2023) - Scheda informativa sull'Antimonio. CRMs 2023, https://scrreen.eu/crms-2023/.

Flotation-based beneficiation of Rare Earth Minerals from granite quarry waste: reagent and regrinding effects

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Keywords: flotation, quarry waste characterisation, Rare Earth Elements.

This work explores the potential of flotation as a complementary technique for further beneficiation of Rare Earth Minerals (REMs) from the Montorfano and Baveno granite quarry waste (Piemonte, Italy). Laboratory-scale batch flotation tests were performed on magnetic pre-concentrates ground to 100 µm, targeting the separation of REE-bearing minerals (i.e., allanite, monazite, and xenotime) from the gangue minerals, mainly consisting of biotite (annite-siderophyllite variety) and chlorite (chamosite variety). The influence of different reagents and operating parameters on REMs floatability was investigated, with particular emphasis on the selectivity between annite-siderophyllite gangue and allanite, being similar in chemical composition. Sarcosine- and hydroxamate-based collectors were tested via stepwise addition, in combination with the frother, both with and without sodium silicate as depressant. Experiments were conducted in a 2 L mechanically agitated flotation cell at 20% pulp density, under various pH conditions adjusted with Na_2CO_3. Tests were replicated on feed material subjected to wet regrinding at 50% solids in a rod mill, with increasing times to improve mineral liberation. Feed samples were characterised by ICP-MS, XRD, and automated mineralogy using TESCAN Integrated Mineral Analyzer (TIMA), providing a comprehensive overview of chemical composition, phase distribution, mineral associations, and liberation of REMs. Flotation concentrates and tailings were initially analysed using XRF for rapid screening on Rare Earth Elements (REEs) to plan subsequent tests, while selected samples were submitted for further characterisation by ICP-MS. Among the tested reagents, the amphoteric surfactant Atrac 922 emerged as the most effective collector in terms of REEs grade and recovery, with promising performance at both neutral and basic pH, and a cumulative REEs recovery of around 70%. Compared to the tests without regrinding, flotation products obtained from re-ground material show the highest REEs grade with an enrichment ratio of ~2.5 from feed to concentrate, despite slightly lower recovery (~50%). The cumulative recovery data for REEs, Fe, and K suggest a good selectivity between target and gangue elements in flotation concentrates; however, a relevant amount of REEs remained in the tailings. Mineralogical characterisation of flotation products will help define whether further grinding may enhance the overall recovery. Nonetheless, finer particle size may lead to entrainment effects (Wang et al., 2015) and require adjustments to reagent dosages and other flotation parameters, such as pH, temperature, air flow rate, or pulp density. Therefore, additional optimisation studies will follow to identify the ideal combination of operating conditions to maximise REMs grade and recovery.

Wang L. et al. (2015) - A review of entrainment: mechanisms, contributing factors and modelling in flotation. Miner. Eng., 70, 77-91, https://doi.org/10.1016/j.mineng.2014.09.003.

From groundwater to crystals: hidden radioactivity in the fibrous epsomite of the abandoned Perticara Sulphur Mine

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Keywords: epsomite, neoformed minerals, radioactivity.

The abandoned Perticara Sulphur mine (Central Italy) was developed in the Gessoso-Solfifera formation and it has been widely explored by cavers due to its geological significance. Recently, the discovery of newly-formed fibrous epsomite within the mine has attracted attention because of its potentially hazardous effects. However, little attention has been paid to the effects on human health, and these studies represent only the first steps towards understanding this emerging research field. Recently, it has been discovered that the fibrous epsomite crystals may contain significant concentrations of toxic elements (As, Co, Fe, Mn, Ni, Sr, Ti, Zn) and, surprisingly, high levels of radioactive isotopes, such as ^{210}Po and ^{210}Pb (Giordani et al., 2022, 2024).

The peculiar confined environment of this abandoned mine has been analysed with the main goal of identifying the source of the toxic and radioactive elements. To this end, fibrous epsomite and other mineralogical components (e.g., sericolite, host-rock, bitumen) were analysed. Previous results highlighted that, among all samples collected within the mine, only the fibrous epsomite exhibited high concentrations of the radioactive ^{210}Po and ^{210}Pb isotopes. Other constituents, such as bitumen, also showed relevant ^{210}Po activity, in equilibrium with ^{210}Pb wherease sericolite and the host-rock showed the concentrations typical of surface soils. A slight anomaly of ^{40}K and ^{226}Ra contents was observed only in the host-rock, probably related to a higher presence of ^{40}K and ^{238}U in the original rock formation.

However, the mechanisms responsible for the selective accumulation of radioactive elements within the fibrous epsomite crystals remain unknown.

This study seeks to advance the understanding of the complex migration mechanisms of ^{210}Po and ^{210}Pb from the host rock to the newly formed epsomite. To achieve this goal, the surrounding environment has been geochemically characterised using alpha and gamma-spectrometry, XRD, XRF, and SEM, through the analyses of the four main lithologies outcropping around the mine. Additionally, U and Ra concentrations were analysed in the groundwater, sampled inside the mine, to provide a comprehensive view of the hydrogeological regime. to provide a comprehensive view of the hydrogeological regime.

Preliminary results indicate that the major radionuclides (^{238}U, ^{232}Th) in the surrounding rocks may be the main sources of ^{210}Po and ^{210}Pb as decay daughters. The formation of epsomite crystals appears to be driven by groundwater circulation, which is enriched in these radioactive elements.

Future research will focus on determining whether these conditions and mechanisms can be optimised and extended to other mineralogical phases for the accumulation of other important elements, such as those considered critical raw materials.

Giordani M. et al. (2022) - Could soluble minerals be hazardous to human health? Evidence from fibrous epsomite. Environ. Res., 206, 112579, https://doi.org/10.1016/j.envres.2021.112579.

Giordani M. et al. (2024) - High-levels of toxic elements and radioactivity in an abandoned sulphur mine: Insights on the origin and associated environmental concerns. Sci. Total Environ., 906, 1167498, https://doi.org/10.1016/j.scitotenv.2023.167498.

A potential reserve of critical raw materials in the Sabatini geothermal field, Italy

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Keywords: Sabatini, Boron, REE.

The Pleistocene Sabatini Volcanic Complex (~800–70 ka; Marra et al., 2020) hosts a geothermal field that has recently attracted renewed research interest due to its potential for lithium-rich hydrothermal brines in Italy. Beyond lithium, however, the metasomatic calcsilicate (skarn) rocks that host these brines may also hold economic significance as potential sources of critical raw materials (CRMs). Critical raw materials are essential resources for modern society, valued for their economic importance, supply risk, unique properties, and environmental and social implications. Among these, rare earth elements (REEs) are vital to emerging technologies, playing a key role in enhancing energy efficiency and driving digital innovation.

Using core and cutting samples from the ENEL-SH2 borehole (depth = 2498 m), we characterized the in-depth mineral assemblage of the skarn rocks and assessed the vertical distribution of REE-bearing minerals (vesuvianite, garnet, and titanite) to estimate the potential CRMs reserve. This was achieved through a multidisciplinary approach combining microtextural analysis, X-ray diffraction (XRD), electron microprobe analysis (EMPA), and laser ablation ICP-MS.

Within the 1400–1650 m depth interval, (REEs, Th, U, B)-rich vesuvianite and wiluite are the dominant mineral phases, with an average modal abundance of 20 vol%. Vesuvianite in this zone shows an average B content of ~7500 ppm, a high total REEs concentration (~7500 ppm), and an average uranium content of 113 ppm. These preliminary results highlight the economic potential of hydrothermal mineralization in the Sabatini geothermal field, suggesting it may represent a strategic REEs reserve and a significant repository of CRM in Italy.

Marra F. et al. (2020) - Monti Sabatini and Colli Albani: the dormant twin volcanoes at the gates of Rome. Sci. Rep., 10, 8666, https://doi.org/10.1038/s41598-020-65394-2.

Sediments washing for mercury and total petroleum hydrocarbons removal: laboratory- scale tests

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Keywords: K_2FeO_4, SDBS, sediment washing.

Contaminated marine sediments with organic and inorganic pollutants are major environmental concerns due to anthropogenic activities in and around harbors, necessitating stringent treatment to meet regulations on reuse and mitigate environmental burdens from toxic pollutants (Bolan et al., 2023; Yang et al., 2024). This research investigates innovative remediation techniques using potassium ferrate (VI) (K_2FeO_4) as a strong oxidant combined with the surfactant Sodium Dodecyl Benzene Sulfonate (SDBS). Jar tests were conducted to evaluate the efficacy of oxidant- and surfactant-enhanced sediment washing for mercury and TPH removal. Furthermore, the aim of this study is to evaluate the applicability of Fe(VI) in the process of chemical oxidation enhanced with surfactants in a marine sediment contaminated by mercury and hydrocarbons.

This approach utilized 1 L beakers, each containing 100 g of sediment and 500 mL of distilled water, the tests varied the concentrations of sodium dodecyl benzene sulfonate (SDBS) surfactant (0.1%, 0.2%, 0.4% w/w) with potassium ferrate (K_2FeO_4) oxidants (0.5%, 1%, 1.5% w/w). The system was mixed at 200 rpm for 5 min, then agitated at 90 rpm for 48 h, with oxidants added after 24 h.

Total petroleum hydrocarbons (TPH) were extracted using a Speed Extractor E-916, following the ISPRA (2011) protocol for C > 12. The resulting liquid extracts were concentrated using a Büchi Syncore Polyvap evaporator. After evaporation, the concentrates were subjected to purification via column chromatography. Subsequently, 1.5 mL of the filtered eluate was collected in appropriate vials and analyzed by gas chromatography with flame ionization detection (GC-FID). Mercury concentrations were determined using a DMA-80 direct mercury analyzer to assess the efficacy of chemical and mechanical remediation treatments. Initial contaminant levels were 19.06 mg/kg for mercury and 783,914 mg/kg for TPH.

The data demonstrates the influence of varying concentrations of Fe(VI) and the surfactant SDBS on the removal efficiencies of Total Petroleum Hydrocarbons (TPH) and Mercury (Hg). TPH removal was most effective with Fe(VI) 0.5% and SDBS 0.2% (95.42%), but the addition of SDBS generally enhanced Hg removal at the cost of slightly reduced TPH efficiency. Notably, Fe(VI) 1% with SDBS 0.4% showed a strong balance, achieving high Hg removal (55.32%) while maintaining good TPH efficiency (84.89%). Increasing Fe(VI) to 1.5% combined with SDBS (0.1–0.4%) further optimized the overall performance, with TPH efficiency exceeding 90% and Hg removal peaking at 44.75%. These results suggest that synergistic use of Fe(VI) and SDBS can enhance Hg remediation while sustaining effective TPH degradation, with the optimal condition appearing at 1.5% Fe(VI) and 0.2% SDBS. Fe(VI) with SDBS effectively removes TPH and Hg from marine sediments.

Bolan S. et al. (2023) - Surfactant-enhanced mobilization of persistent organic pollutants: potential for soil and sediment remediation and unintended consequences. J. Hazard. Mater., 443, https://doi.org/10.1016/j.jhazmat.2022.130189.

Yang H. et al. (2024) - Towards sustainable futures: a review of sediment remediation and resource valorization techniques. J. Clean. Prod., 435, https://doi.org/10.1016/j.jclepro.2023.140529.

Geoaccumulation and persistence of Total Mercury (THg) in soils from Artisanal and Small-scale Gold Mining (ASGM) areas in the Jardim do Ouro District, Brazilian Amazon

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Keywords: ASGM, mercury, Brazilian Amazon.

Mercury (Hg) usage in Artisanal and Small-scale Gold Mining (ASGM) is a major source of environmental contamination in the Brazilian Amazon, significantly impacting ecosystems, human populations, and animal health (e.g. Teixeira et al., 2021). In ASGM, Hg^0 is used to amalgamate gold and then burned off, releasing vapor to the atmosphere that later settles in soils and water bodies, where it can transform into methylmercury and bioaccumulate in food webs (Crespo-Lopez et al., 2021). This study investigated total mercury (THg) concentrations in soils (aliquots of 150 g, 0-10 cm depth) from three ASGM sites in the surroundings of Jardim do Ouro district (6°15'17.58"S, 55°46'8.90"W), within the municipality of Itaituba, Pará State, Brazil. The studied areas included a historical site abandoned 30 years ago (n = 37), a site decommissioned in January 2024 (n = 15), and an active ASGM site (n = 15). Samples were homogenized, frozen and lyophilized. After lyophilization, samples were grounded manually using a ground mortar. THg content was analyzed using Atomic Absorption Spectrometry with pyrolysis. The historical site exhibited the highest Hg mean concentration (1,246 ppb), followed by the recently decommissioned site (134 ppb), which was closer to the regional background (184 ppb), while the active ASGM site had the lowest level (77 ppb). Such a significant difference observed between the historical and active sites ($p = 2.58 \times 10^{-5}$), indicates long-term Hg persistence in soils combined with historical mercury utilization before the establishment of the competent legislation on Hg usage—e.g. the Decree No. 97,507/1989 (Brazil, 1989). The geoaccumulation index showed that 46% of the samples from the historical site (n = 17), 93% from the active ASGM (n = 14), and 100% from the recently deactivated site are non-contaminated. In addition, only one sample from the active site was considered non- to moderately contaminated, while the historical site had at least one sample included in all 6 classes. THg retention in the historical ASGM was strongly associated ($R^2 = 73\%$) with fine particles (< 105 µm), consistent with the presence of clay minerals such as kaolinite identified by X-Ray Diffraction (XRD) and Fourier-Transform Infrared Spectroscopy (FTIR). Soil pHs in samples from all sites (6.5–7.5) suggest low organic matter content, consistent with Thermogravimetry and Differential Scanning Calorimetry (TG/DSC) findings. Our results highlight long-lasting environmental legacy of ASGM on soil Hg contamination, as well as the role of soil mineralogy, particularly the presence of fine particles and clay minerals, in enhancing Hg retention. Understanding these factors is crucial for assessing mercury mobility from soils to other environmental compartments—such as re-emission to the atmosphere or transport to aquatic systems—as well as its environmental persistence and the resulting One Health risks to both ecosystems and human populations in the Brazilian Amazon.

Brazil (1989) - Decree No. 97,507 of 13 February 1989, https://www2.camara.leg.br/legin/fed/decret/1989/decreto-97507-13-fevereiro-1989-448256-publicacaooriginal-1-pe.html.

Crespo-Lopez et al. (2021) - Mercury: what can we learn from the Amazon? Environ. Int., 146, 106223, https://doi.org/10.1016/j.envint.2020.106223.

Teixeira et al. (2021) - Artisanal gold mining in the eastern Amazon: environmental and human health risks of mercury from different mining methods. Chemosphere, 284, 131220, https://doi.org/10.1016/j.chemosphere.2021.131220.

Valorization of rock extraction wastes as a potential source of CRM: the example of REEs in the Buddusò (Sardinia) granite quarries

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Keywords: critical raw material, wastes, REEs.

The Critical Raw Materials Act underlines the urgency and need for cooperation within the European Union to establish a fully integrated and resilient supply chain for critical raw materials, with the aim of achieving autonomy for domestic demand within 2030. In response, several exploration campaigns have been launched across EU territory to identify sites suitable for the extraction of critical and strategic raw materials. The ARTU project ("Sviluppo di un processo di sepARazione innovativo per la valorizzazione degli inerti contenenti materiali sTrategici per l'industria eUropea – POR FESR") focuses on the development of industrial processes to recover valuable strategic materials from inert wastes. Specifically, granite quarry wastes from Buddusò (Sardinia, Italy) were analyzed as potential secondary source of rare earth elements (REEs).

Preliminary investigations indicated total concentrations of rare earth elements in the granite quarry wastes in the range 80-268 mg/kg. OM and SEM/EDS observations revealed that REEs (particularly La and Ce) occur in allanite, from 100 μm to 500 μm in size, always included within biotite crystals. Based on these preliminary results, some tests were performed to obtain REE enriched fractions, combining granulometric and magnetic separation methods. We demonstrated that best separation conditions occur for 63-500 mm grain size range, and for magnetic fields deriving from current from 0.3 to 0.6 Ampere. The resulting concentrates are biotite and allanite enriched, providing total REE concentrations as high as 3300 mg/kg.

Future investigations will focus on chemical or hydrometallurgical techniques for extracting REEs from the allanite concentrate and to evaluate the environmental and economic performance of the overall process through life cycle analysis.

The results of the ARTU project contribute therefore to the objectives of the CRM Act. From an environmental perspective, this project is also in line with the Waste Framework Directive, which emphasizes waste reduction, reuse and material recovery. By developing a process that switches quarry rock wastes from landfill and revalues it through REE extraction, the project not only supports and improves sustainable resource management but also adds economic value to existing mining operations.

Pre-Variscan to post-Variscan metallogeny: lessons from the basement of Sardinia

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Keywords: metallogenic province, crustal fertilization, metallogenic inheritance.

Metallogeny studies the formation of ore deposits across space and time (Pohl, 2022), by investigating their connections with geodynamic settings and petrological processes, while also reconstructing sources, transport and entrapment of metals in mineral deposits (Mineral System Analysis; Wyborn et al., 1994). With its excellent Paleozoic basement exposition and a complex geological history, Sardinia may offer numerous insights to verify the concepts of modern metallogeny. In the main metallogenic provinces of SW and E Sardinia, four metallogenic epochs from Cambrian to Post-Variscan times occurred. The first metallogenic epoch developed during early Cambrian and includes large SEDEX to MVT mineral systems in the SW. The characteristic Pb-Zn-Ba geochemical endowment of this province reflects extensive fluid flow at shallow crustal levels in a probable extensional tectonic setting, with inferred metal sources from a non-exposed Proterozoic basement.

The second is associated with the Ordovician tectonic evolution, that in the SW Sardinia province caused remobilization/supergene alteration of Cambrian ores, whereas in the E Sardinia province led to crustal fertilization (Cu-Sb-As-Au and other elements) due to subduction, mantle/crust interactions and arc magmatism. Ordovician deposits, such as Ti-Zr-LREE-bearing paleoplacers hosted in E Sardinia late Ordovician successions (a true REE metallotect), are related to Katian large scale erosion of the magmatic arc.

The third is linked to the late-Variscan extension in late Carboniferous-early Permian, including crustal melting, granitoid emplacement and widespread hydrothermal activity. The Variscan Mineral System of Sardinia includes orogenic-type As-Au-Sb-W deposits with an inferred age of 300-305 Ma in E Sardinia only, and granite-related F-Sn-W-Mo-Bi deposits at 290-285 Ma in both provinces (Naitza et al., 2024). This metallogenic evolution is an indication that the two provinces, until then separated, assembled in a single block at some time during this interval. Possible metal sources were Cambrian-Ordovician ores and basement rocks, as well as an older, deep-seated basement, as suggested by granites geochemical features (Conte et al., 2017).

The fourth relates to post-Variscan times (late Permian to Mesozoic), arguably related to Tethys opening and the relative large-scale fluid flows at shallow crustal levels. The formation of giant polymetallic and F-Ba-Pb vein systems (e.g., Montevecchio and Silius) may have resulted from metal remobilization from the huge and polyphase metallogenic inheritance of the basement.

Overall, a metallogenic approach and recently implemented knowledge on Cambrian to Post-Variscan metallogenic epochs and their stages of crustal fertilization and mineral deposit-forming activity (metallogenic peaks) in the SW and E Sardinia metallogenic provinces contribute to setting the base for new regional scale resource mapping, ore deposit modeling and mineral exploration.

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Naitza S. et al. (2024) - Post-collisional tectonomagmatic evolution, crustal reworking and ore genesis along a section of the Southern Variscan belt: the Variscan mineral system of Sardinia (Italy). Minerals, 14, 65, https://doi.org/10.3390/min14010065

Pohl W.L. (2022) - Metallogenic models as the key to successful exploration — a review and trends. Min. Econ., 35, 373-408, https://doi.org/10.1007/s13563-022-00325-3.

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A sustainable mining process: extraction of critical minerals from waste while capturing CO_2

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Keywords: CCS, CO_2 mineralization, critical minerals.

The extraction of essential raw materials, known as critical minerals (CMs), is crucial for advancing renewable energy systems and storage technologies. These valuable resources are concentrated in limited global locations and are often obtained through inefficient and unsustainable methods. Current supply chains are inadequate to meet projected future demands. Consequently, there is a growing need to explore innovative and sustainable approaches to sourcing these materials from alternative, more widely available resources, such as waste streams.

In this study, we showcase findings from our investigation into developing an innovative process. This process combines the extraction of critical minerals (CMs) with ex situ carbon dioxide (CO_2) mineralization. For our research, we utilized mine tailings obtained from a wollastonite quarry located in New York, USA, as our source of waste material. The tailings contain three major minerals: wollastonite ($CaSiO_3$), diopside ($MgCaSi_2O_6$), and garnets (grossular $Ca_3Al_2(SiO_4)_3$ and andradite $Ca_3Fe_2Si_3O_{12}$). We conducted enhanced mineral dissolution of the waste material using a flowthrough system equipped with online sensors. The process employed organic acids (oxalic, citric, and formic) as catalysts, with concentrations ranging from 0.001 to 0.1 M, at temperatures of 40°C and 80°C. The extracted elements were then separated using nanofiltration performed by commercial polyether sulfone (PES) membranes modified via the interfacial polymerization method. This resulted in two distinct streams: one containing critical minerals (CMs) - specifically Al, Fe, Mg, and Mn - and another rich in Ca for CO_2 mineralization. Following separation, the Ca-rich fluid was reacted with CO_2 through seeded crystallization using residual mine tailings. This process was carried out at 1 bar of CO_2 partial pressure and 40°C to sequester carbon into calcium carbonates. To describe and analyze the experiments, we developed a mathematical model that combines a population balance equation (PBE) model with geochemistry. This model shows good agreement with the experimental data and indicates that the integrated process reaches steady state within 48 hours. It achieves an extraction efficiency of 80% in one day at 80°C, with complete crystallization occurring within a few hours at 40°C.

Overall, the results from this work lay the foundation for research in new mining processes which address the environmental legacy of earlier operations while opening the possibility for sustainable mining with carbon-neutral or even negative activities.

Geochemical prospecting of fluvial sediments from the Emilia Romagna region for potential secondary CRMs reservoir

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Keywords: CRMs, sediments, geochemical prospection.

The energy transition in Europe is a pivotal aspect of the current agenda, with the supply of Critical Raw Materials (CRMs) being equally crucial. These materials are essential for renewable technologies' components, such as batteries, wind turbines, photovoltaic systems, fuel cells, and robotics (Bobba et al., 2020). This contribution is framed in a large national project aims to develop innovative methods to secure CRM supplies within EU borders, ensuring a stable and sustainable supply chain. Ensuring an internal supply not only reduces dependence on third countries but also strengthens economic security and promotes technological growth. The study is addressed to evaluate the role of river sediments in providing a resource of critical metals, that in a near future could be commutated in a reserve. The explored area is in the Emilia-Romagna region in the Northern Apennines, Italy. This region is known for its significant geological potential, hosting mafic/ultramafic rocks (ophiolites) associated with the External Ligurian Succession (Kiss et al., 2023). The largest reserves worldwide of metals, such as Cu, Ni, Co, PGE, Cr, Ti, and V are strictly related to these rocks (Barnes, 2023) therefore geochemical and mineralogical investigations were made on mafic sediments from four different river systems (Taro, Nure, Dragone, Scoltenna) of ophiolitic basins. Samples are sieved and grounded to powder before making both glass discs and pressed pellets for XRF analyses of major and trace elements for each of the major grain sizes. Absolute density (ρ) is determined with Helium pycnometer and range between 2.67 and 2.73 g/cm^3. Minerals separation is performed using both a Frantz magnetic separator and heavy liquid solution. Each magnetic separated fraction was observed under binocular microscope and fully chemically characterized. Transition metals and Mg are one order of magnitude higher in the magnetic fractions, mainly composed of magnetite, chlorite and serpentine group minerals, compared to the nonmagnetic one, which retains Si, Ca and Sr and is composed mainly of calcite, quartz and feldspars. Heavy liquid separate is ~1% weight is mainly constituted by garnet and oxides.

XRF results show some CRMs metals such as Cr (up to 1000 ppm), Mn (up to 2000 ppm), Ni (up to 500 ppm) enriched in the sand while others such as Cu (up to 50 ppm) and Zn (up to 150 ppm) are enriched in the mud. These values are "anomalous" compared to the sediments of the Po River as their metals concentration is up to four times higher than those observed in sediments collected along the main course of the Po River and ophiolite-free basins such as the Reno River (Amorosi & Sammartino, 2014).

Streams and small rivers flowing near ophiolitic rocks (such as those in the Taro, Nure, Dragone, and Scoltenna catchments) show interesting potential for further investigation on the mineral chemistry of the mafic phases in selected granulometric fraction to evaluate the potential metal reserve.

Amorosi A.& Sammartino I. (2014) - Tracing provenance and pathways of late Holocene fluvio-deltaic sediments by heavy-metal spatial distribution (Po Plain–Northern Apennines system, Italy). In: Scott R.A., Smyth H.R., Morton A.C., Richardson N. (Eds), Sediment Provenance Studies in Hydrocarbon Exploration and Production, 386, Geological Society, London, Sp. Publ., https://doi.org/10.1144/SP386.6.

Barnes S.J. (2023) - Lithogeochemistry in exploration for intrusion-hosted magmatic Ni-Cu-Co deposits. Geochem. Explor. Environ. Anal., 23, 1, https://doi.org/10.1144/geochem2022-025.

Bobba S. et al. (2020) - European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. Critical raw materials for strategic technologies and sectors in the EU: a foresight study, Publications Office, https://data.europa.eu/doi/10.2873/58081.

Kiss G. et al. (2023) - Tracing the Source of Hydrothermal Fluid in Ophiolite-Related Volcanogenic Massive Sulfide Deposits: A Case Study from the Italian Northern Apennines. Minerals, 13(1), 8, https://doi.org/10.3390/min13010008.

Gemological study of agate chalcedony from Civezzano (Trento province, Italy)

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Keywords: agata, moganite, CT-opal.

This paper presents a gemological, geochemical and petrographic study of agate-quality chalcedony from modest volcanic outcrops near Civezzano (Trento, Italy). Chalcedons are hosted in the Permian Buss Formation, which consists of highly hydrothermalised, black, grey-green, or violet-grey porphyritic andesitic lavas (Avanzini et al., 2010). The samples come from two locations, near Penedallo and near Garzano, both close to the important Calisio tectonic line, where the lavas are tectonised and have a brecciated appearance.

80 samples were collected, distinguished by the colours purple, red and orange. Eleven cabochons were obtained from the raw samples, on which gemological, petrographic, SEM-EDS, Micro-Raman spectroscopy, trace element and colorimetric analyses were performed.

The agate chalcedony analysed in this work is of the "lagoon" type. It is a nodular, banded and very fortified agate: the bands form lobes directed towards the centre of the nodule. The colouring is primary in all agates except the purple vein, where it is secondary. Chalcedony is lenght fast type (optical axis is perpendicular to fibre elongation) and lenght slow type (optical axis is parallel to fibre elongation). These agates are characterised by alternating fibrous and spherulitic structures of chalcedony, granular quartz, abundant calcite, subordinate calcite-derived dolomite, pyrite and chalcopyrite.

The red and violet colours are due to the presence of inclusions of iron oxides or traces of elemental iron; orange is related to the presence of iron hydroxides. There is the presence of non-chromophore elements such as Ge, Sb, As. Ge and Sb are present in all colour type agates, especially in the violet and in range respectively. B traces could originate from the andesitic rock or from the interaction of hydrothermal fluids with the rock. As is present in the violet vein.

Micro-Raman analysis higlight the main component is microcrystalline α-quartz, accompanied almost always by moganite, a silica metastable polymorph (Moxon & Ross, 2004; Gotze et al., 2021). The presence of fibrous chalcedony α-quartz, CT opal and moganite would indicate different ages of the three types of agates characterised by a LT hydrothermal event (80 to 120°C; Zhang et al., 2020). CT opal would represent intermediate phase between amorphous and crystalline silica. Absorption micro-Raman spectra of the violet samples exhibit traces of CT opal and moganite; the latter is very abundant in orange agates; the red agates spectra hilight very crystalline α-quartz and absence of moganite.

We therefore hypothesise a hydrothermal genetic scenario in which the structural reorganisation would transform the CT opal into quartz α; the moganite would be formed in quartz-intergrowth and would later be transformed into chalcedony and quartz α.

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CRMs in Central Italy's LREE-F-Rich Belt: a potential REE resource?

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Keywords: critical raw materials, fluorspar, ore deposits.

Recent advancements in green and sustainable technologies, particularly for decarbonisation and the energy transition, have led to a growing demand for critical raw materials (CRMs). In response, the European Commission is encouraging exploration for economically viable CRM deposits. The LREE-F-rich belt of the Roman Comagmatic Province (RCP; Washington, 1906) has emerged as a promising target (e.g., Stoppa et al., 2016), hosting key sites such as the Pianciano deposit (RM), which features a fluoritite and F-Ca carbonatite orebody, currently the largest underdeveloped fluorite resource in Western Europe, and Santa Maria di Sala (VT), characterised by F-Ca carbonatite. These localities exhibit significant concentrations of LREEs and other critical materials, such as barite, suggesting their potential for CRM recovery.

Here we present the preliminary results of a comprehensive geological, geochemical and hyperspectral survey carried out over these study areas, including the first detailed mapping of the Santa Maria di Sala deposits.

The Santa Maria di Sala deposit covers an area of about 2.5 km^2 around the Olpeta stream. In its northern sector, the deposit is continuously exposed, whereas in the southern sector it has a more heteropic character, intercalated with volcanic deposits. The deposit is characterised by a very fine grain size and displays variability in composition and relative abundance of primary constituent minerals.

XRPD and SEM analyses reveal dominant mineral phases including fluorite, calcite, and barite, with subordinate apatite group minerals, clay minerals, Pb- and Mn-carbonates, zeolites, spinels, and rare pyroxenes, garnets, and feldspars.

XRF and ICP-MS data for Pianciano deposit indicate REE concentrations of ~1700 ppm in fluoritite and ~500 ppm in F-Ca carbonatites. SWIR (Short-Wave Infrared) hyperspectral surveys were conducted both in-field and in-lab. After pre-processing, diagnostic absorption features at 1400 and 1900 nm (OH and H-O-H), 2206 nm (Al-OH), and 2330 nm (CO_3^{2-} overtones), together with an unidentified band at 1775 nm were detected. To be noted, the spectral characteristics of these bands, such as band depth and band area, can be strongly influenced by the grain size of the material, making their practical use challenging.

Preliminary extraction tests on the most fluorite-rich samples using HCl under variable conditions showed that HCl achieved up to 60% recovery of LREEs. Optimization of extraction protocols for more efficient REE recovery is ongoing.

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A new geodatabase of mining waste dumps in Sardinia (Italy): a tool for the identification and potential valorisation of Critical and Strategic Raw Materials (CRM and SRM)

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Keywords: metallogenic map, secondary resources, secondary raw materials.

The growing demand for Critical and Strategic Raw Materials (CRM and SRM) at the European level has renewed interest in mining waste deposits as potential secondary sources of supply, identified as Secondary Raw Materials. In Sardinia (Italy), despite its long and rich mining history, no specific database dedicated exclusively to mining waste dumps has ever been developed. The only available dataset (PRAE - Regional Plan of mining activities, 2013) provides a limited mapping of waste deposits, often including natural debris (screes or landslide deposits) mistakenly classified as mining dumps and excluding many relevant sites.

This study presents the first geodatabase entirely dedicated to Sardinian mining waste dumps, created to identify and characterise these deposits with a focus on their potential CRM and SRM content, following the guidelines of the Italian Legislative Decree 84/2024 (Italian Government, 2024).

The database was built using QGIS software and Microsoft Excel, integrating 15 key parameters for each waste dump: ID, geographic location, name, geological map sheet, waste type (classified into six categories based on the mining process), grainsize of waste materials, surface area, lithological substrate, type of mineralisation, exploited minerals, geochemical association, presence of CRM and SRM, owner of the mining licence (mining company), activity period, type and magnitude of environmental interactions (e.g., acid mine drainage, erosion processes).

Spatial analysis and dump identification were carried out using multiple data sources: historical aerial imagery (1954-2019), geological maps, the PRAE database, mining concession layers, online resources (minieredisardegna.it, mindat.org), bibliographic research, and 3D visualisation tools (Google Earth) which were fundamental for accurately delineating the dumps and distinguishing them from natural deposits. About 1900 mining dumps have been identified, of which approximately 1400 (73%) are in the macro-area of Sulcis-Iglesiente-Fluminèse-Arburèse.

Each mining waste dump is represented by a triangular symbol (recalling the shape of a waste pile) whose colour will reflect the presence of an associated CRM or CRM group. The geodatabase represents a tool for future mineral exploration, resource recovery planning, and environmental monitoring of mining areas in Sardinia. This work represents a definite step forward compared to previous databases, as it is the first study to systematically consider mining waste dumps as potential mineral resources — a component entirely neglected in the two previous editions (Ente Minerario Sardo, 1978; Tocco et al., 2008) of the Metallogenic Map of Sardinia. Moreover, it provides a methodological model replicable in other Italian mining districts, supporting a sustainable approach to managing mineral resources and mining heritage.

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Re-assessing historical mine wastes in Sardinia (Italy): a potential source of critical and strategic raw materials

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Keywords: circular economy, REE mineralogy, SEM–XRD analysis.

In the context of the European Critical Raw Materials Act (European Commission, 2023) and Italy's National Exploration Program (DL n. 84/2024*),* historical mine wastes are gaining increasing attention as potential recoverably sources of Critical and Strategic Raw Materials (CRM/SRM). The green and digital transitions and emerging strategic sectors, such as e-mobility and renewable energy, have heightened the demand for such materials. With its long mining history, Sardinia hosts numerous mine waste deposits that remain largely unexplored regarding their CRM/SRM potential.

This contribution presents preliminary results from mineralogical and microanalytical investigations carried out on selected historical mine waste sites located within the Arburèse and Fluminèse districts (SW Sardinia). The study is focused on residues from mines that exploited hydrothermal Pb-Zn-Ag and F-Ba ores, including Montevecchio (Sanna and Telle mineworks), S'Acqua Bona, Santa Lucia, and Su Zurfuru. Analytical techniques include X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM), used to identify carrier phases of economically relevant materials.

The analyses reveal the presence of both primary and secondary Pb-Zn minerals, such as galena [PbS], sphalerite [ZnS], cerussite [$PbCO_3$], anglesite [$PbSO_4$], pyromorphite [$Pb5(PO_4)_3Cl$], and hemimorphite [$Zn_4Si_2O_7(OH)_2 \cdot (H_2O)$], and the presence of CRMs like barite [$BaSO_4$], fluorite [CaF_2] and REE. The REE-bearing phases, include phosphates (e.g. monazite [$(Ce,La,Nd,Th)PO_4$], xenotime [YPO_4]) and fluorocarbonates (e.g. bastnäsite [$(Ce,La)(CO_3)F$], synchysite [$Ca(Ce,La)(CO_3)_2F$]) and are commonly associated to the quartz gangue as well as zirconium and titanium oxides (zircon [$ZrSiO_4$], rutile, anatase, and brookite [TiO_2]).

These findings testify the variety of raw materials that can be found in the historical mine wastes, some of which were never exploited (REE). Therefore, Sardinian mine wastes are on the spot for the current exploration interest as a raw material source, and exploration models focused on secondary raw materials and circular economy strategies. Future research will integrate geochemical assays, spatial analysis, and tonnage estimation to assess recovery potential and environmental co-benefits.

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Close-range hyperspectral sensing of mineralized outcrops in open pit mines: analysis of the lithocaps of the Allumiere-Tolfa epithermal system (Central Italy)

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Keywords: VNIR-SWIR spectral imaging, minimum wavelength mapping, lithocaps.

This study aims to demonstrate how the new generation of portable spectral cameras can significantly enhance geological mapping, enabling rapid acquisition of detailed mineralogical information directly in the field. We showcase the Allumiere-Tolfa mining district (central Italy), where lithocaps associated with a high-sulfidation epithermal system are characterized by alunite and polymetallic mineralizations in addition to a widespread, structurally-controlled and zoned hydrolytic alteration of the hosting volcanic rocks (Marchesini et al., 2024).

High spatial and spectral resolution reflectance VNIR-SWIR imaging was acquired on four outcrops in two open-pit mines using tripod-mounted Headwall Photonics cameras, covering the spectral range between 400 and 2500 nm, with 270 (VNIR) to 166 (SWIR) spectral bands. These spectral images were complemented with 3D modelling obtained via drone imagery and Structure from Motion reconstruction (Tavani et al., 2024). Hyperspectral data were validated through laboratory spectroscopy and mineralogical analysis on twenty-nine ground samples. Identification and characterization of optically active minerals were performed using minimum wavelength mapping and band ratios (Laukamp et al., 2021; Thiele et al., 2021). Distinct hydrothermal alteration zones were mapped by using absorption features of smectites, kaolin-group, and alunite-group minerals at ~2160, 2200, and 2290 nm in the SWIR range. The high-resolution spectral data allowed to: (1) discriminate among kaolinite polytypes (i.e., kaolinite and dickite) based on the OH absorption wavelength position in the region around 1380-1400 nm, (2) investigate the alunite composition through the shift in the band positions of the sulfate-related absorptions between 1400-1800 nm. The derived spectral parameters enabled the estimation of the physicochemical conditions (i.e., temperature and pH values) under which the hydrothermal alteration developed. The signature of Fe-oxy-hydroxides at ~900 nm allowed mapping the supergene alteration. The hyperspectral images of the Allumiere quarry were finally draped onto a 300-m wide 3D model, for improving the spatial visualization of the alteration facies and their relationship in 3D with tectonic structures and other geological features.

This high-resolution, multi-scale approach, combined with 3D modelling, provided key insights into the geometry of alteration mineral assemblages, proving to be a powerful tool for the rapid, cost-effective, and detailed characterization of exposed vertical wall-rocks. This methodology can be readily applied to other active and/or inactive mining areas.

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A metallogenic model for the Piani Resinelli Zn-Pb deposit (Lombardy, Italy)

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Keywords: alpine-type deposits, southern Alps, hydrothermalism.

The Alpine-type deposits (APT) represent a subclass of the well-known Zn-Pb Mississippi Valley-type deposits. They constitute a large metallogenic province located between Italy, Austria, and Slovenia, including the well-known districts such as Bleiberg, Mezica, Raibl, Salafossa, and Gorno districts. The APT deposits have a long mining history spanning from Roman times to the early 1990s. Total metal production exceeding 6 Mt Zn+Pb from a resource exceeding 110 Mt of ore. The renewed interest in base metals, and especially the by-products associated with this deposit type (Ge, Ga, In, Tl) has stimulated renewed exploration activities in some districts. The Piani Resinelli deposit represents the westernmost expression of APT deposits in Italy and is hosted in the Ladinian-Carnian stratigraphic succession of the Lombardian basin (Southalpine Domain, north Italy), mainly composed of peritidal limestones (Calcare Rosso; Breno Fm.). We present here a metallogenic model based on a large set of data obtained from field work, petrography, fluid inclusions analyses, radiometric dating, isotopic and geochemical analyses. This research is likely to contribute to a better understanding of the genesis of the ore deposits hosted in the Lombardian Basin, and more generally of the APT deposits.

In situ U-Pb geochronology on ore-associated carbonates revealed a late Carnian-early Norian age for the sulfide mineralization and an Early Jurassic age for the latest calcite cements. Meso- and microscopic observations showed that the precipitation of the ore in the deposit was accompanied by a complex series of processes (dolomitization, silicification, brecciation, dissolution, cementation), suggesting intense fluid circulation in the Ladinian-Carnian stratigraphic succession of the Lombardian Basin at a relatively shallow burial depth. Fluid inclusion microthermometry indicates hydrothermal fluids involved in ore formation were moderately hot (Th: 51-164°C) and highly saline (7.8–22.5 eq. wt% NaCl+$CaCl_2$), belonging to the NaCl-$CaCl_2$-H_2O system during ore precipitation. Isotopic analyses revealed that the ore-forming fluids most likely evolved from seawater to high salinity brines through fluid-rock interactions, while the reduced sulfur was provided mainly by bacterial sulfate reduction (BSR).

The resulting metallogenic model involves the presence of high salinity, modified seawater leaching metals from the Southalpine basement and/or the overlying volcano-sedimentary Permian cover, and then flowing upward up to the Anisian-lower Carnian stratigraphic succession of the Lombardian Basin along extensional and strike-slip faults during seismic events. The most likely precipitation mechanism is the mixing of the hydrothermal metal-rich fluid with a connate seawater enriched in reduced sulfur by interaction with organic-rich shaly levels (e.g. those occurring at the base of the Gorno Fm.) that percolated downwards into the precipitation site during inter-seismic periods.

Evaluating CRM potential and environmental impact of Sardinian mining and metallurgical waste: the cases of Su Suergiu and Corti Rosas antimony mines (Southeastern Sardinia)

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Keywords: CRM, Sardinia, antimony.

The supply of Critical and Strategic Raw Materials (CRM, SRM) is a key challenge for the EU. To reduce dependency on third countries, the Critical Raw Materials Act (2024) sets targets for domestic sourcing and recycling from extractive waste, which represent the second-largest source of waste in EU, with about 622 million tons produced annually (Eurostat, 2023). Much of this waste comes from abandoned mining sites, where it was stockpiled for years, posing significant environmental hazards. Yet, these wastes may contain significant amount of SRM and CRM, which could now be considered for recovery.

In Italy, Sardinia is a key area of interest due to its rich mining legacy and the considerable volumes of mining waste left behind after the closure of the last active mines, which hold significant CRM potential. Specifically, this study focuses on evaluating the potential of mining waste in the Gerrei area (SE Sardinia), where about 1 Mm^3 of mining and metallurgical residues were disposed in dumps (Naitza et al., 2019). The study investigates the Su Suergiu and Corti Rosas mines, which represented the largest industrial complex for antimony in Italy until the 1980s. Our research has confirmed that the metallurgical slags at Su Suergiu are significantly enriched in Sb (up to 9.75 wt%) and could be viable for its recovery. In contrast, flotation tailings from Corti Rosas generally show lower Sb concentrations, ranging between 0.1 and 5 wt%, still of interest for further investigation of its recoverability. In addition to Sb, these wastes contain other valuable metals in potentially useful concentrations, such as Zn (up to 4.47 wt%), W, and Au (up to some g/t according to Garbarino et al., 2003). Finally waste rock dumps show metal contents too low to envisage any possibility of recovery.

A major environmental concern at both Su Suergiu and Corti Rosas is the presence of alkaline drainage (pH 8-11), mainly originating from Na-rich slags and from flotation tailings. This atypical basic leachate, unlike classic Acid Mine Drainage (AMD), promotes the mobilization of other potentially toxic elements such as Sb and, As, whereas the only AMD yielding sample largely mobilizes Zn and Cu. Contaminated runoff flows into local streams (Rio Sessini and Rio Ciurixeda at Su Suergiu) and then discharges into the Flumendosa River. This river, the largest in southeastern Sardinia, also receives input from Corti Rosas and other minor mining sites in the Gerrei district, resulting in a contamination plume extending over ~20 km to the Tyrrhenian Sea (Fancello et al., 2023, and references therein).

Our results showed that the slag samples (Su Suergiu) are potentially the most polluting waste, with tailings at Corti Rosas mine being the second, while contribution from waste rocks is negligible. The recovery of these metals is important and could be feasible even in subeconomic conditions, considering how strongly it would reduce the environmental pollution in this area.

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Characterization and CRM evaluation in an abandoned silver mining district: the case of Monte Narba, SE Sardinia

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Keywords: Sardinia, CRM, silver.

The increasing demand for Critical and Strategic Raw Materials (CRM and SRM) represents a major challenge for the European Union, because of its dependence on non-EU-countries suppliers. In response, the EU adopted the Critical Raw Materials Act (May 2024), which promotes the sourcing and recovery of valuable materials from alternative and domestic sources, such as extractive waste (EW). In EU, EW account for nearly 622 million tons per year and represent the second-largest waste stream (26.6% of total share, according to Eurostat 2023). Much of this waste is largely associated with abandoned mining areas, posing environmental concerns but also holding the potential for CRM and SRM re-evaluation. Sardinia (Italy) represents a strategic area of interest due to its rich mining legacy and the substantial volumes of mining waste left behind after the closure of the last active mines, which hold significant CRM potential. This study focuses on the Monte Narba mining site, located a few kilometres south of San Vito and Muravera, in southeastern Sardinia (Sarrabus region). Mining in this area began in the second half of the 19th century. Monte Narba was the largest of the silver deposits in Italy, producing—at its peak—approximately 800–1,000 tonnes of high-grade silver ore per year. After manual sorting, the ore was crushed and gravity-enriched on site, producing two main concentrate fractions: one with Ag contents of 1.5–2.5 wt%, and another with 0.35–0.7 wt% (Mezzolani & Simoncini, 1889). Recently, the Monte Narba site attracted interest due to the presence of industrial minerals such as barite and fluorspar, both CRM, which in the past were considered waste, but today could be subject to economic recovery. Despite the renewed interest in the valorisation of these materials, detailed information on the status of mineral dumps remains limited. The available knowledge is mainly based on historical documents or surveys, which have identified two main types of waste: a main landfill with a volume of approximately 82,820 m³, mainly hosting waste rocks, and a second area of fine waste, resulting from hydrogravimetric separation, stockpiled in an area of 46,657 m² and a volume of 93,314 m³ (Regione Sardegna, 2003).We carried out a systematic sampling campaign, during which 16 samples were collected, mainly from the fine waste stockpile. Additionally, 3 samples of heterogeneous waste (probably a mix of processing fines and waste rock) were gathered from areas upstream to the mining yard, near old mining adits. Preliminary XRF data show that the fines waste is enriched in Ag (500-600 ppm), together with Pb (0.9-1.2 wt%), Zn (1.3-1.9 wt%), F (6.9-8.7 wt%) and Ba (0.2-0.3 wt%). These results agree with the presence of galena, sphalerite, barite and fluorite in the dump bodies, as suggested by historical documents. Occurrence of fluorite and barite is confirmed by SEM-EDS first investigations performed on selected samples, which also evidenced the presence of LREE phosphates associated to quartz; pyrite is Ni-enriched. Further analyses (optical microscopy, XRD analysis, SEM-EDS) are currently underway to investigate texture and mineralogy of the waste materials. In addition, the study focuses on analysing potential environmental impacts by performing laboratory tests to simulate the release of metals into the environment, with a focus on the type of drainage through leaching tests (SPLP procedures).

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Can we achieve sustainable minerals supply chains? A Sub-Saharan African scenario

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Keywords: Africa, development minerals, cement.

During the last few years we witnessed the exposure of the raw materials market to disruption of supply chains due to global events and changing geopolitical scenarios. Moreover, the supply of primary resources by mining, quarrying and other extractive activities has a huge impact on the environment, due to depletion of resources, direct impact on geomorphic dynamics, emission of greenhouse gases, and increasing pressure on landfill facilities.

The need of addressing the above issue is summarized in Sustainable Development Goal 12, which states the need to "ensure sustainable consumption and production patterns". In particular, targets 12.1, 12.a and 12.c explicitly mention the role of developing countries in this scenario. Within the emerging economies, those of the African continent, and particularly Sub-Saharan Africa, will play a key role.

Africa is known for its enormous richness in high-value mineral resources, including precious metals, gemstones and critical minerals. Despite the export of such high-value minerals represents a significant share of the GDP of many African countries, the net economic effect of exporting mineral resources with no added value and importing value-added processed goods is negative (Mwiti Marangu et al., 2023). Moreover, the extraction of critical minerals is often associated with illegal activities, lack of safety and exploitation of child labour. On the other end of the mineral resource spectrum, non-metallic or industrial minerals can play a key role in the development of Sub-Saharan Africa. Recently, they were also defined Development Minerals and considered to be "economically important close to the location where the commodity is mined. In comparison to minimally processed export-minerals, they have closer links with the local economy with a more direct impact on poverty reduction" (Franks, 2020). In fact, this category of minerals represents 40% by mass of all extracted raw materials, and is mostly incorporated into the construction industry (Valentini et al., 2022). As the continent with the highest urbanization rate in the world, Africa is witnessing a surge in the demand for construction materials. But paradoxically, a continent with such a richness in high-value mineral resources is poor in a low-value resource such as limestone, which is the primary raw material for cement production. This leads to a conflicting situation in which Sub-Saharan African countries are forced to import cement, which contributes to the high local cost of this essential material and hinders the supply of houses and infrastructure. This contribution will explore the potential of Sub-Saharan Africa of setting up a local construction industry by exploiting alternative and locally available raw materials for cement production, which include industrial and agricultural waste. This may also potentially lead Africa to play a key role in the development of a more sustainable mineral supply chain and construction industry.

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The Predazzo Cu-W deposit revisited (Dolomites, Eastern Alps): an A-type-granite-related magmatic-hydrothermal system?

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Keywords: mineral deposit, triassic magmatism, southern Alps.

The Bedovina Cu-W deposit consists of chalcopyrite–scheelite stockworks developed over lengths of ca. 200 m along the contact between intrusive and volcanic rocks of the Triassic Predazzo magmatic complex, which have been mined for Cu and, since 1909, for W until the middle of the 20th century (Frizzo et al., 2010). The Predazzo complex consists of monzogabbro to quartz-syenite and granite intrusions (238–236 Ma) and abundant, essentially coeval, volcanic rocks with calcalkaline-shoshonitic affinity, along with volumetrically minor but widespread alkaline dykes and lavas covering a wider age interval (238–203 Ma; Nardini et al., 2025; Visonà et al., 2025). Various hypotheses have been proposed for the genesis of the Bedovina deposit. Considering only the latest works, based on the polyphase nature of the mineralization and its geochemical features, Frizzo et al. (2010) suggested an early high-temperature hydrothermal W stage (scheelite + tourmaline + quartz + K-feldspar ± cassiterite) related to S-type granitoids, followed by a Cu stage (chalcopyrite ± pyrite, sphalerite, galena, sulfosalts) related to I-type calcalkaline granitoids. Based on the strict spatial association with phonolite dykes (one dated at 234 Ma) intruding the main volcanic sequence, Nardini et al. (2025) suggested instead a genetic link with the alkaline magmatism.

One of the least studied lithotypes in the area is the tourmaline granite that cuts all other calcalkaline–shoshonitic rocks ca. 1 km to the east and south of the Bedovina deposit. On-going petrographic and geochemical analyses and field work revealed that this granite is a peraluminous A-type granite (e.g., 15-70 ppm Nb, 30-60 ppm Y, strong negative Ba, Sr and P anomalies). Based on our observations and on detailed 1990's exploration data (Eni-Aquater, 1997), the western sector of the granite forms a deeply hydrothermalized (albite, muscovite, sericite, chlorite), subvolcanic cupola intruding into the shoshonitic volcanic rocks. In this sector, the granite is scheelite-bearing and exhibits widespread orbicules and minor pockets containing a similar mineral parageneses (tourmaline, chalcopyrite) as the Bedovina stockworks. Disseminations of cassiterite occur in the most differentiated and hydrothermalized portions and in aplitic veins. The striking mineralogical compatibility (both W and Cu ± Sn) between the tourmaline granites and the Cu-W stockworks strongly suggests a direct genetic relationship. Based on present data, the involvement of a distinct I-type granitoid or of phonolitic magmas appears unnecessary. As a working hypothesis, we suggest that the relatively young, barren phonolite dyke accompanying the main Bedovina stockwork postdates the mineralization and intruded along the same weakness structure that previously controlled the migration of the hydrothermal fluids.

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Multi-stage fluorite mineralization in the Southern Alps: new insights from the Vignola deposit

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Keywords: fluorite, southern Alps, mineral deposit.

The increasing demand for critical materials essential to the energy transition has led to renewed interest in abandoned mining sites. The Trentino-Alto Adige (Italy), with over 200 such sites, represents a significant area for investigation. These deposits are mainly composed of polymetallic veins, often characterized by dominant fluorite, barite, quartz, or carbonate gangue, with minor occurrences of pegmatites and magnetite ore bodies. Geological evidence suggests that the mineralizing events can be linked to two magmatic phases. The older phase is associated with Permian post-Variscan events that affected the Southern Alps (e.g. Bakos et al., 1972). Permian ore bodies are mainly hosted in the lower part of the Athesian Volcanic Group (e.g., Zaccon deposit), or at the contact between igneous rocks and the metamorphic basement (e.g., Vignola and Cinquevalli deposits; Bakos et al., 1972). Triassic deposits may be linked to the Predazzo magmatic event and are represented by veins that cut through Ladinian dykes and are hosted in the upper part of the Athesian Volcanic Group (e.g., Prestavel deposit; Bakos et al., 1972).

This contribution presents new data on the Permian deposit of Vignola that consists of four NE–SW-oriented veins, mainly composed of fluorite, quartz, and sulphides (primarily sphalerite and galena). The mineralization occurred in three main stages (Di Colbertaldo, 1965). The first stage took place during the final phases of the Variscan orogeny, which created NE–SW fractures filled by alternating quartz and fluorite, with minor sulphides, from circulating hydrothermal fluids. A second, localized geodynamic event (possibly related to Triassic magmatism) reopened these fractures, resulting in renewed mineralization, characterized by fluorite and quartz (± siderite). This second stage contains more sulphides than the previous one (Di Colbertaldo, 1965). The final stage formed a N20E oriented vein composed mainly of barite (± fluorite and ± calcite), which crosscuts and displaces the older mineralized structures (Di Colbertaldo, 1965).

The fluorite recently collected from both mine waste and directly from the galleries of the third vein occurs primarily as green to light blue crystals, often cube-shaped, while transparent and light pink varieties are rarer. SEM cathodoluminescence reveals complex crystallization patterns, including both sectoral and concentric zonation. EDS analyses show the presence of REE rich accessory minerals hosted both in the fluorite and quartz. Consistent with the cathodoluminescence, in-situ LA-ICP-MS data conducted along crystal growth zones reveal variable REE concentrations, which can be broadly categorized into three distinct patterns corresponding to different mineralization stages of the deposit. The integration of in situ and bulk geochemical analyses with detailed mineralogical characterization will support a comprehensive assessment of the deposit's economic potential.

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S21.

Energetic georesources and storage: advancing sustainable energy transition through exploration, development, and storage technique

CONVENERS AND CHAIRPERSONS

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Preliminary results of hydrogen injection and batch reaction tests on rock salt and kainite samples from the Realmonte Mine: simulation and feasibility of storage cycling

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Keywords: rocksalt, H_2 storage, salt caverns.

Hydrogen storage in salt caverns is a promising strategy for large-scale energy storage, but its feasibility depends on a detailed understanding of how hydrogen interacts with the host rock. Consequently, assessing storage feasibility requires thorough geochemical, mineralogical, and petrophysical characterization of the salt formation. In this study, we characterized twenty rock salt samples (a mixed sample of halite and kainite comprising 60% kainite, 30% halite, and 10% potassic minerals) from the Realmonte mine in southern Sicily, before and after controlled hydrogen exposure to evaluate their suitability for underground hydrogen storage. Hydrogen injection and extraction cycles were simulated in the laboratory under confining pressures of 3.8-19.2 MPa, with hydrogen gas at 8 bar, to mimic a range of subsurface cavern conditions. Additionally, batch reaction tests were performed on seven samples (mixed sample of halite and kainite) at 10 MPa for 5 days without confining pressure, representing static hydrogen exposure scenarios equivalent to depths of approximately 200-1000 m. Pre- and post-exposure analyses employed a comprehensive suite of techniques, including geochemical analysis of major, minor, trace, and rare earth elements; mineralogical analysis; thin-section petrography; mercury intrusion porosimetry and X-ray computed tomography (XCT).

Preliminary results show minimal geochemical alteration: elemental compositions and mineral phases remained largely unchanged after hydrogen cycling, indicating negligible chemical reactivity with the host rock. However, notable petrophysical changes were observed: microstructural analysis revealed grain boundary reorganization in the salt matrix, and porosity measurements indicated an evolution of the pore network. These findings suggest that while the salt's chemistry remains stable, repeated hydrogen pressurization can subtly modify the rock's physical structure. Overall, our findings align with existing literature on hydrogen-salt interactions and support the feasibility of hydrogen storage in salt caverns. The negligible geochemical impact observed is encouraging for the integrity of the salt formation, whereas the observed physical changes highlight the need for continued monitoring and further investigation at larger scales. Collectively, these results underscore the importance of detailed pre- and post-injection characterization and will inform future field-scale hydrogen storage trials in salt caverns.

Mechanisms of "unexpected" fault reactivation during gas storage operations: a numerical investigation

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Keywords: numerical modeling, geomechanics, faults.

Initially developed to store methane (CH_4) for balancing seasonal demand in natural gas supply, underground storage systems have since evolved to include carbon dioxide (CO_2), to support decarbonization targets, and hydrogen (H_2), to provide a buffer against the intermittency of renewable energy sources. However, the use of faulted reservoirs raises geomechanical safety concerns, particularly regarding the reactivation of pre-existing faults during subsurface operations, potentially triggering (micro-)seismic events.

This work presents a detailed geomechanical numerical investigation of fault stability during gas storage, with a specific focus on the Rotliegend formation in the Netherlands, where fault reactivation has been recorded not only during primary production, but also during cushion gas injection and cyclic CH_4/H_2 storage operations, as well as CO_2 permanent storage. These events occurred under pressure conditions already experienced in earlier phases and are therefore classified as "unexpected".

To investigate these phenomena, we adopt a 3D finite element – interface element (FE-IE) model, in which faults are represented as internal discontinuities governed by a Mohr-Coulomb failure criterion, enabling a realistic macro-scale simulation of fault activation under quasi-static conditions. By analyzing multiple geometric and mechanical configurations, we identify key factors, including geological settings, geomechanical properties, and reservoir operating conditions, that increase the likelihood of fault reactivation.

Our results demonstrate that fault slip during both cyclic and non-cyclic gas storage operations is more likely to occur if (i) reactivation has already taken place during primary production, and/or (ii) reservoir pressure approaches specific critical thresholds. This work contributes to defining safe operational pressure windows for storage phases, providing guidance for the design of underground energy storage systems.

Joint geophysical modelling constrained by geological and petrophysical data for assessing the geothermal energy potential of the Romagna and Ferrara folds (RFF), Eastern Po-plain

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Keywords: geothermal energy, Romagna and Ferrera folds, ingeo project.

Advancing geothermal energy, the thermal energy stored within the earth's crust, supports global efforts to reduce carbon emissions and offers a sustainable solution to meet the rising energy demand. However, developing this resource requires a comprehensive assessment of the geothermal prospect to mitigate the risks and high costs associated with drilling non-productive wells. The InGEO (Innovation in GEOthermal resources and reserves potential assessment for the decarbonization of power/thermal sectors, www.ingeo.cnr.it) project seeks to develop an innovative exploration workflow for integrating geological, geophysical and petrophysical datasets that will contribute to reducing these uncertainties. The project focuses on the Northern Apennine buried - structures belonging to the Romagna and Ferrara Folds (RFF). Analysis of borehole data identified a thermal anomaly within this region attributable to deep fluid circulation within the deep-seated Mesozoic carbonate sequences. In this study, we present a joint interpretation of geophysical data. Firstly, previous seismic tomography models (Magnoni et al., 2022; Kastle et al., 2025) were integrated with sonic velocity data obtained from wells drilled in the RFF region (Livani et al., 2023) using the Fuzzy c-means method to develop a consistent cluster model. Secondly, gravity data (Zahorec et al., 2021) over the RFF region were inverted to implement a density contrast model using the GROWTH-23 inversion technique. The resulting 3D density contrast and cluster models were jointly interpreted to investigate the shallow and deep structures within the RFF region. The models were constrained with a 3D geological model (well logs, seismic lines, stratigraphic columns) and petrophysical data (thermal and acoustic measurements on rocks) obtained on outcrops also sourced from the RFF region. This information will be used as input parameters for the development of a thermal model and the implementation of an open-source and web-based GIS tool that will assess the deep geothermal resource potential for both hydrothermal resources and closed-loop deep heat exchangers solutions in Italy, but with potential to extend the approach in different geological contexts. The workflow of InGEO project will be used as a decision support system for developing geothermal projects in Italy.

InGEO is a PRIN 2022 PNRR Project and has received funding from the European Union, Next Generation EU.

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Seismological characterization of a Hot Dry Rock geothermal system in the Gonghe basin, China

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Keywords: geothermal exploration, induced seismicity, fractured zone characterization.

In response to the rise in the world's energy demand and the need to reduce carbon emissions, the past two decades have seen a significant transition from fossil fuels toward renewable energy exploration, that include a focus on geothermal energy and its subsurface reservoirs. However, since natural geothermal resources are not uniformly distributed and not always accessible for direct use, EGS and HDR have been developed to extend the potential for geothermal energy production even in areas with less favorable geological conditions.

One of the most recent Hot Dry Rock systems in China is located within the Gonghe basin, in the Northeastern part of the Qinghai-Tibetan Plateau. The geological complexity (Tang et al., 2022) of the area has facilitated the uplift of a granitic body characterized by limited natural fluid circulation and a high geothermal gradient, with temperatures reaching 236°C at a depth of 3.7 km (Zhang et al., 2024). To extract the heat and generate energy, high-pressure water started to be injected in 2019. Despite the significant benefits of geothermal applications, one of the main concerns related to fluid injection is the potential for triggering seismic events.

A surface network of 20 three-component seismometers has been installed to monitor the induced seismicity during the stimulation period between June and October 2021, in which the system recorded 2,615 micro seismic events. The catalog was later expanded to over 10,000 events through advanced automatic detection algorithms. To perform further investigation, we selected 204 earthquakes with a magnitude higher than 0.7 (the maximum M_L for the catalog is 3.3). These events were analyzed using: I) shear wave splitting (SWS) (Wuestefeld et al., 2010) method to characterize the fracturing of the area in terms of fracture orientation and degree of anisotropy, II) focal mechanism solutions to better constrain the faults plane orientation and local stress field, III) waveform similarity analysis through cross-correlation, and IV) event relocalisation using the Double-Difference (DD) method (Waldhauser, 2001).

The obtained results show that the fast S-wave polarization has a NE-SW direction parallel to the maximum horizontal principal stress, suggesting that the injection stimulated pre-existing fractures rather than generating new microstructures. The cross-correlation analysis was used to identify clusters characterized by waveform similarity and spatial proximity. For each cluster, a representative master event was selected as a reference to relocalise the events using the DD technique.

Finally, we integrate these analyses with a PSTM cube derived from a 3D seismic reflection survey. These combined datasets were used as a preliminary guide for the delineation of major structural features. This integrated approach aims to assess the fault slip potential of the identified structures under future injection scenarios, to better understand their possible contribution to injection-related seismic hazard.

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Evaluating the influence of the hydrodynamic characteristics of groundwater in the thermal performance of different geothermal borehole configurations

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Keywords: geothermal energy, borehole heat exchangers, numerical simulations.

Debates on climate change mitigation and the geopolitical developments of the last three years requires a faster decarbonisation of the heating and cooling sector, which is still responsible for 49% of the final energy consumption in Europe (Goetzl et al., 2022). Geothermal energy represents a vital and promising option, by substantially decreasing the energy consumptions and costs especially if included into decarbonized heating and cooling grids (Chicco et al., 2022). A proper design is then of paramount importance to guarantee the energy performance of the system.

This work deals with the optimization of the technical and geometrical characteristics of borehole heat exchangers (BHE) in a well-defined hydrogeological context of the NW Italy, aimed at the integrating the space heating and cooling of buildings. Three different configurations were analysed by investigating their thermal performances according to available geological information that revealed an aquifer in the first 36 m, overlying a poorly permeable marly succession. Numerical simulations were used to validate the geological, hydrogeological, and thermo-physical models by back-analysing the experimental results of a Thermal Response Test (TRT) on a pilot 150 m deep BHE. Five-years simulations were then performed to compare 150-m and 36-m polyethylene 2U, and 36-m steel coaxial BHEs. Results show higher thermal power extractions in the shallower 2U BHE (56.03 W/m) compared to the deeper one (42.47 W/m), probably due to presence of the aquifer which surely plays an important role in increasing the thermal power. The coaxial configuration shows the best performance both in terms of specific power (74.51 W/m) and borehole thermal resistance (0.02 mK/W). Knowing of the detailed hydrogeological conditions allowed understanding how the hydrodynamic characteristics of the groundwater can significantly increase the thermal efficiency, and how the best coupling between the geological framework and technical requirements, ensures the best energy performance and economic sustainability, avoiding deeper and more expensive drillings.

Chicco J.M. et al. (2022) - Improving the efficiency of district hating and cooling using a geothermal technology: underground thermal energy storage (UTES). In: Calabrò F., Della Spina L., Piñeira Mantiñán M.J. (Eds), New Metropolitan Perspectives. Lecture Notes in Networks and Systems, Springer, 482, https://doi.org/10.1007/978-3-031-06825-6_164.

Goetzl G. et al. (2022) - Pathways to better integrate geothermal energy at its full technological scale in European heating and cooling networks. Eur. Geol., 54, 44-50, https://doi.org/10.5281/zenodo.7882918.

Analyses, interpretation, and integration of boreholes data and seismic reflection profiles into a 3D Geological Model of the Romagna and Ferrara Folds, (Eastern Po Plain) for the evaluation of geothermal resources

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Keywords: geothermal energy, Romagna and Ferrara folds, ingeo project.

Geothermal energy is a constant, clean, and renewable energy source that utilizes the Earth's internal heat for different applications, such as heating, cooling, and electricity generation. However, the estimation and exploitation of this energy implies to acquire a deep knowledge of the rocks composing the reservoirs and those overlying it.

The InGEO project ("Innovation in GEOthermal resources and reserves potential assessment for the decarbonisation of power/thermal sectors"; www.ingeo.cnr.it) seeks to develop an innovative exploration workflow integrating geological, geophysical, and other datasets to enhance the characterization of reservoir rocks and their sedimentary cover. This approach supports strategic planning for deep geothermal resource utilization in Italy.

Deep-seated carbonate reservoirs, forming the basement of sedimentary basins, are key targets for geothermal development. In the eastern Po Plain, the buried Romagna and Ferrara Folds (RFF)—stretching from the Emilia Folds to the Adriatic coast and from the northern Apennines to the undeformed Po foreland—show significant geothermal gradient variations, indicative of convective heat flow in deep carbonate units. Low geothermal gradients (14°C/km) within the carbonate reservoir and higher gradients (53°C/km) in overlying impermeable formations indicate thermal convection within Mesozoic carbonate units (Pasquale et al., 2013).

For the evaluation of the geothermal potential of the area, the implementation of a consistent 3D geological model, displaying the thickness variations of the major lithological units of the area, is crucial. To this aim, we have digitized and analyzed over 200 seismic surveys (VIDEPI database, www.videpi.com), 700 deep boreholes (> 1500 m deep; CNR database, www.geothopica.igg.cnr.it), and 160 borehole logs (sonic and lithological; Livani et al., 2023). Seismic reflection interpretations, constrained by well stratigraphy, were used to identify key lithological unconformities. Age limits maps have been obtained by interpolating well tops and interpreted seismic horizons. The uncertainties of the results increase with the age of the units, due to the decrease of the control points with depth (well tops). These preliminary maps have been converted from the TWT to depth domain, in order to obtain a consistent 3D geological model. The obtained results were compared with those of the previous study of Livani et al. (2023), which focused on the on-shore part of the study area. Our 3D model will be used to constrain the seismic velocities and densities distribution in depth, obtained from the analyses and interpretation of different geophysical datasets (Basant et al., 2025) and become part of a crustal model public available for multiple applications, such as geothermal resources evaluation.

Acknowledgments: The InGEO project is part of the PRIN 2022 PNRR initiative and is funded by the European Union's Next Generation EU program.

Basant et al. (2025) - Joint geophysical modelling constrained by geological and petrophysical data for assessing the geothermal energy potential of the Romagna and Ferrara folds (RFF), Eastern Po-plain. In: Congresso congiunto SIMP-SGI, Abstract book, Padova, 16-18 September 2025.

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Pasquale et al. (2013) - Evidence for thermal convection in the deep carbonate aquifer of the eastern sector of the Po Plain, Italy. Tectonophysics, 594, 1-12, https://doi.org/10.1016/j.tecto.2013.03.011.

Analysis of existing Borehole Thermal Energy Storage installations for optimized design and integration into a District Heating Network in Italy

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Keywords: borehole thermal energy storage, district heating network, lithology.

Heating of buildings accounts for approximately 30% of total energy consumption and 35% of greenhouse gas emissions in EU countries. In response, the European Union has set a net-zero emissions target by 2050 through the Green Deal policy, prompting individual countries to align with this goal. One promising solution is the implementation of small and large scale District Heating Networks (DHNs), where heat from solar irradiation or industrial processes is distributed via underground pipelines and stored in the subsurface. This approach is estimated to save 1.4 million GWh annually and reduce CO_2 emissions from residential and industrial buildings by 400 million tons.

This study was in collaboration with the REHEAT project, financed by Centro Interdipartimentale Levi Cases, Università di Padova, which want to explore the technical, social, economic, and legislative feasibility of DHNs in Italian urban environments. Specifically, this work investigates existing Borehole Thermal Energy Storage (BTES) installations to understand various configurations of borehole heat exchangers, with a particular focus on their spatial arrangement and interaction with subsurface lithology. The goal is to identify optimal design parameters for a simulated case study within the REHEAT project.

Three representative BTES installations were reviewed, each illustrating a different DHN configuration with varying heat sources. These include: the Drake Landing Solar Community in Canada (Mesquita et al., 2017), which uses solar panels and short-term thermal storage tanks; a recent installation in Palermo, Italy (Buscemi et al., 2023), where solar collectors are integrated beneath asphalt in a parking area; and the Emmaboda system in Sweden (Nilsson & Rohdin, 2019), one of the largest BTES installations utilizing industrial waste heat.

The review revealed key design principles for optimization. To minimize heat loss, storage volumes should be cylindrical, with depth roughly equal to diameter, and allow for thermal stratification. Moreover, understanding the subsurface stratigraphy, including fractured rock zones and groundwater flow, is essential for maximizing system efficiency and managing costs. Distributed thermal sensing methods (Galgaro et al., 2024) can help detect these subsurface features. Insights from the literature review helped the selection of parameters for simulating a DHN scenario using the TRNSYS software, as proposed in the REHEAT project.

In conclusion, this study supports the REHEAT project's objectives and provides a basic benchmark for BTES applications. Further investigation into diverse case studies and integration with technologies such as Phase Change Materials (PCMs) is recommended to enhance energy storage performance.

Buscemi A. et al. (2023) - Coupling a road solar thermal collector and borehole thermal energy storage for building heating: First experimental and numerical results. Energy Convers. Manag., 291, 117279, https://doi.org/10.1016/j.enconman.2023.117279.

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Modelling gravity signatures to detect subsurface fluid storage: The GREEN project (Geological stoRagE of hydrogEn and carboN: clean and efficient monitoring methods)

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Keywords: green project, geological storage, monitoring methods.

Decarbonisation and low-carbon fuels are key strategies for achieving the EU's 2050 climate neutrality target. Meeting this goal will require widespread deployment of Carbon Capture, Usage and Storage (CCUS) alongside production and temporary storage of hydrogen. These operations inherently rely on geological and geophysical knowledge and require reliable, cost-effective monitoring techniques to ensure long-term operational safety during and after subsurface activities.

The GREEN project (Geological stoRagE of hydrogEn and carboN) aims to support this effort by evaluating the feasibility of gravity and electromagnetic methods for monitoring underground storage, potentially reducing the high monitoring costs associated with conventional approaches (https://zeroemissionsplatform.eu/).

This study presents gravity modelling based on the Volve field in the North Sea, a depleted hydrocarbon reservoir selected for its comprehensive and publicly available dataset (https://www.equinor.com/energy/volve-data-sharing). A fully parameterised 3D geological model of the Jurassic Hugin Formation was developed to simulate gravity responses under various storage scenarios. The reservoir comprises porous sandstones sealed by Jurassic and Lower Cretaceous shales and is offset by faults, with depths ranging from 2750 to 3120 m. To assess the depth sensitivity of gravity monitoring, three models were constructed at 2750, 1750, and 750 m depth, discretised into 25 × 25 × 25 m cells. Post-production density changes were derived from mass balance calculations incorporating hydrocarbon and brine production and injection data. For leakage assessment, the shallowest model was adapted to include an additional lateral volume representing potential fluid escape.

Forward gravity modelling was performed using the UBC-GIF algorithm included in the Geoscience ANALYST Pro software suite (https://www.mirageoscience.com) to calculate the vertical gravity component (Δg_z) for complete hydrocarbon extraction, post-production brine flooding, CO_2 injection, and H_2 storage with and without cushion gases (CO_2 or N_2). Results show that significant and detectable gravity anomalies occur in the first three scenarios, particularly at shallower depths (e.g. Δg_z up to 96.7 μGal for brine flooding at 750 m) exceeding detection thresholds of modern top-level field gravimeters.

Conversely, simulations of H_2 injection yielded gravity signatures below detection limits (e.g. < 0.4 μGal), underscoring the challenges of monitoring low-density gas storage via gravimetric methods. Scenarios involving partial withdrawal of cushion gas generated only minor signatures, detectable solely at shallow depths.

Overall, modelling results demonstrate the effectiveness of this approach for detecting CO_2 and brine-related mass changes in the subsurface, establishing its viability for CCS monitoring. However, they also underscore the need for further research to adapt and calibrate the method for monitoring low-density fluid storage, such as hydrogen.

Implications for long-term CO_2 storage in saline aquifers: regional-scale pressure and brine flow dynamics in the Silverpit Basin (Southern North Sea, UK)

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Keywords: geological CO_2 storage, saline aquifer, hydrogeological flows.

A large-scale deployment of Carbon Capture and Storage (CCS) is essential to achieving climate targets by mitigating atmospheric CO_2 emissions. To this aim, geological formations with favourable characteristics—particularly extensive saline aquifers—are targeted for long-term storage. However, concurrent injection operations within a shared regional setting can interact, perturbing natural conditions and potentially influencing the performance and safety of individual storage projects (Birkholzer et al., 2009).

Carbon storage licenses have been awarded in the Silverpit Basin in the UK Southern North Sea. Extending over 9,000 km^2, this basin hosts numerous four-way dip structural traps where CO_2 is planned to be injected into the regionally spreading Triassic Bunter Sandstone Formation (https://www.bp.com/content/dam/bp/country-sites/en_gb/united-kingdom/home/images/nep/NEP-Environmental-Statement-Part-A.pdf).

Using seismic and well data, a reservoir-scale model of this laterally continuous aquifer has been developed to evaluate the influence of variable petrophysical properties and boundary conditions. Numerical simulations were performed using a black-oil model across multiple scenarios, simulating injection via 14 wells distributed throughout the licenses at a rate of 1 $MtCO_2$/yr per well for 50 years. Subsequently, CO_2 saturation, pressure evolution and hydrological flows have been calculated for the next 5000 years post-injection period.

Results indicate that CO_2 accumulates at structural highs over decades to centuries post-injection. Regional pressure perturbations generated by injection persist for centuries to millennia, contingent on boundary conditions. Notably, these pressure gradients significantly influence inter-reservoir brine flow, with observed flow reversals occurring once or twice across scenarios. Brine flow rates reached up to 250–300 sm^3/day, depending on the imposed boundary conditions.

This study underscores the importance of accounting for regional-scale pressure and fluid flow dynamics when assessing the long-term performance and security of CO_2 storage. A robust understanding of these processes is vital not only during operational phases but also over extended post-injection timescales, to mitigate unintended migration risks and support economically viable and safe CCS deployment.

Birkholzer J.T. et al. (2009) - Large-scale impact of CO_2 storage in deep saline aquifer: A sensitivity study on pressure response in stratified systems. Int. J. Greenh. Gas Control, 3, 181-194, https://doi.org/10.1016/J.IJGGC.2008.08.002.

Is geothermal energy production possible from tight shallow water carbonates? An example from the Upper Cretaceous Apulian carbonates

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Keywords: geothermal energy, fractures, carbonates.

The shallow water carbonates of the Apulian Platform are prolific reservoirs for hydrocarbons. The relatively homogeneous matrix petrophysical properties go along with the complex structural setting and associated fault and fracture network.

This study focuses on an old hydrocarbon field in Southern Italy that could be converted into a geothermal field for production of hot water and associated energy for local consumption. The Benevento field was discovered in the early 70s. The reservoir units consist of Turonian to Lower Miocene fractured limestones and calcarenites at a depth of around 3000 m TVDSS and bearing both oil and gas. The carbonates are tight having low matrix porosity (avg. 1.4, max 9% - core measurements) and permeability (avg. 1.5 mD and max 73 mD - core measurements) and it is considered to be a fractured reservoir. The trap is structural, defined by a pop-up structure belonging to the buried Apulian thrust belt. The structure lies on the same trend of the larger oil fields in the region (Val d'Agri oil fields).

During the hydrocarbon production it was discovered the complex fluid system within the carbonate reservoir. The upper part of the reservoir is characterised by a gas-condensate mixture mostly made of CO_2 in supercritical condition at reservoir pressure and temperature. Below this fluid there is an oil zone with varying oil gravity and at the bottom of the oil zone there is an active aquifer. The temperature at the top of the reservoir (around 3000 b.s.l.) varies between 130°C and 150°C. The high-water temperature is not local but it is associate to a larger thermal anomaly of the heat flow.

This study on the Benevento field summarises the preliminary results of a potential hydrocarbon-geothermal pre-feasibility technology application as energy transition case. The main objective of the study is to assess the geothermal potential of this fractured carbonate reservoir considering both the matrix and fractures as key players in the storage and fluid pathways of high temperature fluids.

A new dual porosity/dual permeability reservoir model was build integrating old vintage dataset and new methodologies and workflows. Two different scenarios were considered to estimate the size and depth of the hot water reservoirs according to the previous production life of the field depending on degree of depletion and the fluid contacts movement.

Various dynamic and reservoir modelling studies were performed using well tests, fluid, temperature gradients and hydrocarbon production data from the field.

This study shows how important is to have an integrated approach and workflow to assess the geothermal potential of an old hydrocarbon field in fractured carbonate rocks. This study also highlights the main uncertainties to consider when carrying out a pre-feasibility study for a geothermal project in a complex reservoir that was previously developed as a hydrocarbon field.

CCS in carbonate-dominated systems: a multidisciplinary technical workflow supporting projects development

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Keywords: CCS, carbonate reservoirs.

According to the Sustainable Development Goals and the decarbonization process, Eni is already proceeding on several initiatives aimed at CCS within siliciclastic reservoirs. In contrast to their siliciclastic counterparts, carbonate systems are characterized by more rapid and effective fluid-rock interactions, strictly related to their geological nature. Although not fully explored yet, the perspective of injecting CO_2 in carbonate-dominated systems is a real opportunity, considering both current and future projects under development. Eni has an historically strong added value represented by the internal G&G multidisciplinary technical workflows, applied in the last years also to CCS activities. In addition, Eni's structure ensures full control over the entire chain of technical activities from data acquisition and analysis to simulation sensitivities for CCS projects. In this paper we will show the geologically driven guidelines to be followed for the characterization of carbonate systems for CCS. These are achieved using a multidisciplinary technical workflow specifically implemented for carbonate reservoirs, within the scope of an Eni R&D initiative. The integrated experimental workflow (Pisicchio et al., 2024) consists of 5 macro steps: (1) pore network characterization studies based on core, and other wells data, (2) pre-tests rock and fluids characterization, (3) static (ageing) and flow-dynamic (core flooding) tests, (4) post-tests rock and fluids characterization and (5) simulation modeling at different scales (0D to 3D) and by means of different simulation platforms. The presented technical workflow is applied to a specific real case, the current Eni candidates for CCS in carbonates dominated systems. The implementation of the above-mentioned workflow for CCS in carbonate reservoirs has allowed to: i) optimize the timelines of G&G (Geology & Geophysics) studies in support of the project, being now developed through more streamlined technical workflows; ii) minimize the technical and environmental risks associated with injection operations; iii) reduce uncertainties and thereby enhancing risk management and project feasibility.

Pisicchio P. et al. (2024) - Experimental Integrated Workflow Activities for CCS Application. SPE Europe Energy Conference & Exhibition, Turin, Italy, June 2024, https://doi.org/10.2118/220010-MS.

Impact of fracture geometry and connectivity on geothermal reservoir performance

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Keywords: fractured geothermal reservoirs, discrete fracture network, heat extraction efficiency.

The global shift towards low-carbon energy sources has intensified interest in renewable technologies capable of providing stable, long-term power generation. Among these, geothermal energy stands out for its ability to deliver baseload electricity and direct heating with low environmental impact and high reliability. Unlike solar and wind, geothermal systems are not weather-dependent, making them a critical component of a resilient and diversified energy mix. As part of the broader energy transition, leveraging geothermal resources has become increasingly important in unlocking energy from low-permeability or fractured rock formations. Understanding and optimizing the subsurface flow and heat transport in these reservoirs is essential to improve energy extraction efficiency and ensuring the economic viability of geothermal projects.

This study employs Discrete Fracture Network (DFN) modelling to simulate and evaluate the behaviour of geothermal reservoirs with varying fracture geometries, orientations, densities, and connectivity. Using DFNWorks, a robust open-source simulation suite, deterministic and stochastic 3D fracture networks were generated to assess thermal and hydrological processes impact on fluid flow and heat extraction efficiency. Multiple DFN realizations are examined to quantify the sensitivity of energy recovery to fracture heterogeneity, including anisotropic distributions and clustered fracture families. Preliminary results reveal that fracture connectivity and orientation relative to the well pair strongly dictate preferential flow paths and thermal breakthrough times. Highly connected networks enhance permeability and thermal sweep efficiency, while sparse or poorly oriented networks may lead to early thermal short-circuiting and inefficient energy recovery. These findings highlight the importance of detailed fracture characterization in geothermal field development and demonstrate the utility of DFN modelling as a predictive tool for optimizing well placement, stimulation strategies, and long-term reservoir performance. This work contributes to advancing the deployment of geothermal technologies in complex fractured environments and supports informed decision-making in sustainable energy planning.

Study of the possible application of thermo-active sheet piles in Venice Lagoon

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Keywords: sheet piles, energy geostructures, Venice Lagoon.

Shallow low-enthalpy geothermal installations represent a potential high-efficiency solution that exploits the subsurface as a heat source or sink due to its thermal inertia. Through the circulation of a heat transfer fluid in a closed circuit, this system can extract heat from the ground to supply it to users in winter and remove heat from buildings to release it into the ground in summer.

Energy geostructures operate on the same principle, being conventional geotechnical structures incorporating pipes that function as heat exchangers with the surrounding soil. By combining structural and energy functions, the advantages are both ecological-environmental and economic.

Recently, thermo-active sheet piles have been developed, representing an innovative type of EG characterized by an extensive contact area with the soil, also capable of exchanging heat with surface water bodies due to their particular geotechnical application (Ziegler et al., 2019; Gerola et al., 2023). Their thermal efficiency primarily depends on the structure's geometry, thermal properties of the surrounding soil and used materials, and hydro-geological factors influencing the thermal behavior (Gerola et al., 2025). Generally, heat exchange generates temperature variations in the structure itself and its surroundings, potentially leading to thermo-induced stresses and deformations in both the soil and the structure. These must be analyzed in the design phase to ensure the structure mechanical functionality and its long-term energy efficiency.

Currently, the energy sheet pile has been tested in the Netherlands, supporting the bank of a river canal approximately 1.75 m deep. The steel sheet pile had an embedment depth of about 15m and a thickness of 8mm, inserted into lacustrine-marshy deposits resting on a Holocene fluvial sandy layer. The sheet pile was equipped with 2 circuits, one with a maximum depth of 3 m, exchanging heat primarily with the canal water, and a second deep circuit down to 15 m, exchanging heat with both the soil and the canal water. The system was monitored through temperature measurements of structure, soil, and heat transfer fluid, as well as inclinometers to measure any deformations induced by thermal variations. The experimental results were than compared with modeling results, obtaining excellent agreement. The study demonstrated, in the tested case, that the deformation induced by geothermal activation is negligible (2 mm at the top) (Gerola et al., 2025).

The idea for future applications is to create a test site in the Venice Lagoon, where sheet piles are extensively used due to the lagoon bed elevation. The aim is to study the energy and mechanical performance of geothermal sheet piles in this unique environment, characterized by tidal level variations. While awaiting the identification of a location for the test site, a series of simulations will be conducted considering the local climate, hydraulic characteristics of the lagoon, and thermal properties of Venetian soil.

Gerola M. et al. (2023) - Understanding the thermal efficiency of energy Quay Walls: a comprehensive study using field tests and finite element simulations. In: COMSOL Conference, Munich, Germany, November 2023, 1-6.

Gerola M. et al. (2025) - Energy quay walls: Performance analysis and optimisation. Geomech. Energy Environ., 42, 100664, https://doi.org/10.1016/j.gete.2025.100664.

Ziegler M. et al. (2019) - Energy sheet pile walls–Experimental and numiercal investigation of innovative energy geostructures. In: Proceedings of the XVII ECSMGE-2019, XVII European Conference on Soil Mechanics and Geotechnical Engineering, https://doi.org/10.32075/17ECSMGE-2019-0932.

How derisk geothermal projects using hydrocarbon exploration data: the Guardia Lombardi case study (Southern Italy)

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Keywords: geothermal energy, hydrocarbon exploration data, geothermal potential.

The urgent need to reduce greenhouse gas emissions (particularly carbon dioxide; hereinafter CO_2) and to achieve carbon neutrality by 2050, as ratified by the twenty-sixth Conference of the Parties (COP26) to contrast global warming, requires the adoption of concrete and urgent measures, first and foremost the green energy transition.

In this context, geothermal energy represents a highly promising resource capable of significantly supporting the deployment of low-carbon technologies for both building heating/cooling and electricity generation. However, the high economic costs and mining risks connected to the exploration phase hinder its development. Reusing pre-existing subsurface geological data from past hydrocarbon exploration campaigns offers a strategic solution to overcome these barriers and, consequently, promotes the use of geothermal resources.

Italy has considerable geothermal potential relative to its current level of exploitation. Furthermore, its long history of hydrocarbon exploration generated a large amount of subsurface data. Within the scope of the broader European decarbonization agenda, Italy must intensify efforts to capitalize on this green energy resource, even taking advantage of existing oil and gas data.

As a case study, in this work, a 3D geological model of the Guardia Lombardi area (Campania Region, southern Italy) was reconstructed, and the geothermal potential was evaluated by analyzing and interpreting pre-existing subsurface data (i.e., seismic reflection profiles and well data) acquired over time for hydrocarbon exploration purposes. The exploitation potential of the identified geothermal resource was defined with a specific numerical simulation, and a detailed cost evaluation was performed. A buried carbonate anticline was identified as a potential geothermal reservoir, with temperatures reaching 125°C at a depth of only 2300 m. Numerical simulations estimated an exploitation potential of 70 kg/s over a 30-year lifespan. Based on these results, we propose a technical solution for residential heating and/or cooling combined with the production of electricity in the nearby municipality of Grottaminarda. Economic analysis shows a Net Present Value of approximately € 5.2 million and an Internal Rate Return of 15%, further strengthened by the absence of additional data acquisition costs and the mitigation of exploration risks.

The encouraging economic and technical outcomes of this study highlight how the reuse of pre-existing subsurface data can substantially reduce the costs and mining risks associated with geothermal resource exploration. This approach has the potential to accelerate geothermal energy development in already-explored regions, contributing to a faster and more significant reduction in CO_2 emissions (Livani et al., 2025).

Livani M. et al. (2025) - Reusing oil and gas exploration data to derisk geothermal projects: the guardia lombardi case study (Southern Italy). Renew. Energy, 242, 122401, https://doi.org/10.1016/j.renene.2025.122401.

Innovation in geothermal potential assessment: the InGEO Project

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Keywords: geothermal energy, potential, exploration.

Geothermal potential is often cited as immense. According to IEA (2024), geothermal potential is second only to solar PV in terms of electricity generation among renewable energy technologies. It is also significant for heat and cooling production, especially in countries with high heating and cooling demand, and, generally, "more than enough to meet all electricity and heat demand in Africa, China, Europe, Southeast Asia and the United States".

Assessing geothermal potential identifies ideal sites and ensures geothermal project viability; this is the goal of the InGEO project. ("Innovation in GEOthermal resources and reserves potential assessment for the decarbonisation of power/thermal sectors"; www.ingeo.cnr.it). The project's novelty lies in producing an open-source tool for calculating geothermal potential, including thermodynamic simulation and economic analysis of operating plants. InGEO challenges include: (i) developing an innovative exploration workflow that integrates geological, geophysical, thermophysical, and other datasets to enhance geothermal reservoir characterisation; (ii) computing geothermal potential based on resource characteristics and operational solutions for heat extraction and power generation in conventional and non-conventional systems (fluid extraction-reinjection, closed-loop exchangers, thermal storage); and (iii) validating the regional scale approach with site-specific information where geothermal projects are in operation.

The exploration workflow is being established by evaluating geothermal conditions in the Northern Apennines' buried fold and thrust belt, including the Romagna and Ferrara Folds. Over 200 seismic surveys, 700 deep boreholes (over 1500 m), and 160 borehole logs across about 22.500 km^2 have enabled a detailed 3D geological model. This model shows the variation in thickness of main lithological units to roughly 10 km, identified through seismic reflection interpretations guided by well stratigraphy. 3D seismic tomography and surface gravity data models are compared to spot inconsistencies in geophysical parameter datasets and produce a more robust 3D model. This model and petrophysical analyses will form the basis for developing the thermal model and dynamically assessing the area's thermal regime. The open-source code in development, titled GEOTHERMOS, integrates the temporal variations of underground conditions with the production metrics of the plant. It utilises the volumetric method, considering vertical and lateral variations in temperature, static reservoir pressure, and rock permeability distributions. The code can currently simulate thermodynamic cycles for electricity generation and calculate the Levelized Cost of Energy (LCOE) and the Net Present Value (NPV) for the techno-economic evaluation.

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IEA (2024) - The future of geothermal energy, International Energy Agency, https://www.iea.org/reports/the-future-of-geothermal-energy.

The geothermal resources of Lipari and Salina Islands (Aeolian Archipelago, Italy)

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Keywords: geothermal, resources, Salina.

The geothermal potential of selected areas within the Aeolian Archipelago (Salina, Lipari, and Vulcano Islands) is currently being assessed through the integration of existing geological, geochemical, and geophysical data with newly acquired geochemical and isotopic evidence. The ongoing analysis focuses on the characterization of the main hydro-chemical facies, the saturation state with respect to relevant hydrothermal mineral phases, and the estimation of reservoir CO_2 partial pressure. Isotopic measurements (δ^2H, $\delta^{18}O$, $\delta^{34}S$, and ^3H) are being processed to constrain the origin of recharge waters, the source of sulfur, the residence time of water, and potential mixing processes among different hydrothermal and shallow-cold systems. In Lipari, the sampled waters can be classified into 8 distinct geochemical groups (Ca-HCO_3, Na-HCO_3, acidic Ca-SO_4, neutral Ca-SO_4, neutral Mg-SO_4, neutral Na-SO_4, Na-Cl-SO_4 and Na-Cl waters) exhibiting variable salinity, whereas in Salina, the thermal waters display mainly Na-Cl composition characterized by a high-salinity. Overall, the investigated fluids appear to be in disequilibrium with major hydrothermal mineral phases, thereby limiting the applicability of conventional geothermometric approaches. These new data will be integrated with geophysical datasets (e.g., magnetotelluric profiles) to reconstruct the conceptual model of the geothermal system, delineate the main geothermal aquifer and its volume, and assess its geothermal potential. The outcomes of this work, conducted within the framework of the PRIN 2022 PNRR project – GEOTAI, are expected to significantly enhance the understanding and sustainable exploitation of geothermal resources in the Aeolian Islands, contributing to the broader context of the ongoing energy transition.

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Multi-scale faults and fractures characterization in the subsurface combining seismic and well data

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Keywords: faults fractures, seismic attributes, well data.

The characterization of faults and fractures in the subsurface is crucial in many geoscience fields, like oil and gas, mining, carbon capture and storage (CCS), and geofluid storage. Fractures can be characterized at various scales (from centimeters to kilometers in length) using different types of data, such as seismic, outcrop, and well data. However, the characterization of meso-scale faults and fractures (ranging from 10 meters to 1000 meters in length) remains a challenge. These structures often lie below seismic resolution, making them difficult to be detected both by means of seismic attributes and well data. To address this gap, ENI developed a proprietary workflow called T/Frac (Tectonic Fractures Recognition and Characterization), which enables the identification of sub-seismic faults using seismic attributes (such as curvature and continuity). This workflow is based on the premise that structural seismic attributes represent structural features. From these attributes, 2D lineaments are extracted at different depths using an automatic method. These lineaments are then analyzed to calculate key parameters such as length, orientation, density, intensity, and connectivity. Finally, the 2D lineaments are "converted" into a 3D Discrete Fracture Network (DFN) allowing the fracture network to be incorporated into a reservoir model. If available, seismic fault interpretations and well data can be used to further enhance the characterization and extraction of meso-scale fractures and faults. Seismic fault interpretations help identifying the main tectonic events in the study area and provide insights into the primary orientation of geological structures. Well data offer information about fracture sets, type, aperture, position, and stress direction in the subsurface. They are also used to calibrate the DFN extraction from the 2D lineaments.

This study describes a case where interpreted seismic faults, T/Frac workflow, and well data have been integrated to characterize the fracture network in a reservoir affected by salt tectonics. The analysis shows that faults and sub-seismic faults are primarily controlled by extension and salt withdrawal. By extracting sub-seismic lineaments using T/Frac workflow, seven sets of lineaments have been identified. Their orientations are consistent both with features observed in well data and with the area's structural setting. Additionally, fracture length, P21 (fracture intensity) map, P20 (fracture density) map and strain map were extracted for eight geological sequences. Finally, different DFN realizations have been generated and calibrated with the available well data, demonstrating good agreement with features identified through image log interpretation.

Sustainable geothermal solution for the decarbonization of vulcanic islands: case study of Vulcano island (Southern Italy)

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Keywords: geothermal energy, closed-loop heat exchange, coaxial borehole heat exchanger.

Volcanic islands are highly attractive tourist destinations, but their reliance on imported fossil fuels and weak electricity grid connections results in high energy costs and significant environmental impacts. With their volcanic nature, these areas present high potential for the development of geothermal energy. Geothermal energy represents a sustainable and resilient alternative, particularly through closed-loop heat exchange systems, which minimize operational risks while efficiently harnessing subsurface thermal energy. This study evaluates the feasibility and long-term performance of a shallow coaxial borehole heat exchanger (CBHE) on Vulcano Island (Aeolian Archipelago, Italy), characterized by high geothermal gradients and active volcanism. A Geophysical survey has been performed to detect the underground conditions and a finite elements numerical model was developed, by using COMSOL Multiphysics, to analyze heat transfer dynamics, time dependent thermal energy output, in order to simulate the thermal behavior of CBHE systems over a 25-year operational period, under varying injection flow rates, working temperatures, and borehole depths. Simulation results indicate that the CBHEs can achieve stable thermal outputs, reaching pseudo-steady-state conditions. The borehole depth significantly influences heat extraction efficiency, with 1-km CBHE producing up to ten times more energy than a shallower 400-m depth heat exchanger system. Additionally, higher injection flow rates reduce production temperatures due to reduced residence time and the relative heat absorption capability, highlighting the need to optimize flow rate for balancing the amount of electric power production, energy conversion efficiency and pumping costs. Radial temperature distribution analyses show that the thermal influence zone expands over time, reinforcing the importance of sustainable reservoir management to prevent short-term heat extraction depletion. These findings underscore the technical viability of shallow CBHEs in shallow high-temperature volcanic environments as a low-risk alternative to conventional hydrothermal or Enhanced Geothermal Systems (EGS), but the performed analyses also evidence the need of a scrupulous system design and sufficient knowledge of the underground geothermal conditions. The study underscores the viability of shallow geothermal systems in volcanic settings, contributing to the global transition toward low-carbon energy solutions.

Thermally activated recycled concrete as a possible supplementary cementitious material: properties analysis and optimization

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Keywords: thermally reactivated recycled concrete, clinker substitution, CO_2 sequestration.

The cement industry is a major contributor to global CO_2 emissions, responsible for approximately 7% of the total (Glavind, 2009). Emissions mainly derive from fuel combustion to reach kiln temperatures of ~1450°C and from the decarbonation of raw materials (Hasanbeigi et al., 2012). Developing strategies to improve energy efficiency and reduce emissions is thus crucial to achieve the EU's net-zero goal by 2050. This study investigates the potential of thermally reactivated concrete from construction and demolition waste (CDW) as a partial clinker substitute in mortar formulations, aiming to reduce clinker content and enhance CO_2 capture. Starting from a complete preliminary mineralogical characterization of the concrete waste, after thermal reactivation (700°C), clinker phases in the treated samples, in particular C_2S and C_3A, were detected and quantified. Two types of recycled concrete (RC) were examined: material originating from the debris of the 2016 Umbria-Marche earthquake, managed by Valle Umbria Servizi (Norcia) (RC-N), and RC from Manini Prefabbricati S.p.A. (RC-M). The samples were cured and analyzed at 1, 7, 14 and 28 days using X-ray powder diffraction (XRPD), thermogravimetric analysis (TGA), scanning electron microscopy (SEM) and mechanical compressive tests. In the first experimental phase, two mortar series were prepared, each incorporating 20wt% RC (accounting only for clinker phases) as a clinker replacement, with a constant water-to-binder ratio (w/b) of 0.5. Mechanical testing revealed that both series exhibited higher compressive strengths for the control (CTRL) at all curing ages. TGA indicated that RC-N presented an increased presence of C-S-H and Aft phases and a notable reduction in CH content compared to the CTRL, while RC-M showed similar trends only at 28 days. The second phase involves producing mortars with varying RC contents (20wt% and 40wt%) and w/b ratios. In details, mortars with 20% RC replacement are produced with w/b ratios of 0.6 and 0.7, while those containing 40% RC with w/b ratios of 0.7 and 0.8. These samples are under investigation through mechanical tests, TGA and SEM analyses to assess their mechanical and mineralogical properties as a function of water content. Preliminary results indicate RC-M (20wt%, w/b 0.6) exhibits the highest strength among all samples. Subsequent experiments will include accelerated carbonation tests using a Parr Instruments reactor, and analyses on both CO_2 absorption and carbonation's effects on the chemical and physical properties of RC-based mortars. Replacing clinker with thermally reactivated RC reduces CO_2 emissions, raw material extraction, and landfill use. Energy and mass balances of the accelerated carbonation tests will be also evaluated in order to assess the specific energy consumption as a process for CO_2 capture.

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Glavind M. (2009) - Sustainability of cement, concrete and cement replacement materials in construction. In: Khatib J.M. (Ed.), Sustainability of Construction Materials, Woodhead Publishing, 120-147, https://doi.org/10.1533/9781845695842.120.

Hasanbeigi A. et al. (2012) - Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review. Renew. Sustain. Energy Rev., 16(8), 6220-6238, https://doi.org/10.1016/j.rser.2012.07.019.

3D modeling for the determination of geothermal reservoir characteristics in the South-Western Umbria Region, Italy

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Keywords: geothermal reservoir, 3D modeling, geology.

A new geological map has been developed using the regional database created at a 1:10,000 scale by the Geological Section of Regione Umbria. The study area was selected to enhance understanding of the existing geothermal field, based on geophysical and geognostic research conducted by ENEL in the late 1970s and 1980s. This effort aims to improve knowledge of the structure of the potential geothermal reservoir and to determine the possible temperatures within it, continuing the initial work done through the Hotlime project under the European initiative "Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe" (GeoERA). Within the framework of the European project "Geological Service for Europe" (GSEU), 3D geological modeling was performed to characterize the geothermal reservoir beneath an approximately 800-square-kilometer area in the south-western Umbria region of central Italy. The modeling incorporated stratigraphic data and well logs, which were digitized and georeferenced through GIS software, along with the vectorized version of the area's geological map, including geological and tectonic data. Seven significant geological cross-sections were traced at locations with the highest data density. These sections were processed using classic methods and expert opinion, then digitized and incorporated into a 3D modeling software. The study allowed for the reconstruction of subsurface behavior, including the top and bottom of the geothermal reservoir, fault lines, and temperature isolines at 100°C, 150°C, and 200°C, using spatial analysis and data interpolation techniques within the modeling software. The main geothermal reservoir was calculated to be 2.720 cubic kilometers, located at an average depth of -1,700 meters below sea level, spanning an area of about 800 square kilometers. The data layers and documentation related to the geothermal reservoir study will be standardized in line with GSEU Project.

Investigation of deep thermal state in buried Romagna and Ferrara fold sector

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Keywords: temperature data correction, geothermal assessment, thermal state.

With the massive expansion of renewable energy demand, the InGEO Project (Innovation in geothermal resources and reserve potential assessment for the decarbonization of power/thermal sectors) aims at developing and testing an innovative, multidisciplinary exploration workflow to assess the geothermal potential for power generation and direct uses of thermal energy. As case study, the InGEO Project selected the buried Romagna and Ferrara folds sector (Eastern Po Plain, Italy).

The essential parameters for evaluating geothermal resources, in terms of spatial and vertical distribution, are the undisturbed formation temperatures and lithostratigraphic information from deep hydrocarbon and geothermal exploratory wells. In this context, data collection and critical review of the available temperature data are fundamental activities. Different catalogues are available and freely accessible: the Italian National Geothermal Database (Trumpy & Manzella, 2017), the Global Heat Flow Database (GHFD), temperature data from bibliographic sources (Agip, 1977 and following updates), technical reports (consultable from the ViDEPI project website https://www.videpi.com), and scientific studies (Pasquale et al., 2008). Temperature data can be divided into two main categories: Drill Stem Test (DST) and Bottom Hole Temperature (BHT). DST data can be considered representative of the undisturbed thermal regime. Conversely, BHT data usually underestimate the real formation temperature. In this study, we applied different methods to correct the raw BHT data. Time temperature series were corrected with the Horner method (Horner, 1951). In case the circulation time was unknown, we estimated it using the relation proposed by Pasquale et al. (2008).

Following the correction of temperature data, thermal gradient maps can be produced using this dataset. These maps can be spatially correlated with known geological features, such as folds, faults and lithological boundaries, providing valuable insights into subsurface heat flow dynamics. Additionally, thermal modeling will be applied to further refine the interpretation and simulate subsurface temperature distribution, enabling identification of thermally relevant areas to conduce site-specific analyses for geothermal resource assessment.

In conclusion, performing data quality control and applying a robust correction method are essential steps to produce a reliable dataset for assessing the subsurface thermal field and supporting geothermal potential studies through thermal modeling.

Acknowledgments: InGEO is a PRIN 2022 PNRR Project and has received funding from the European Union, Next Generation EU.

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The first Italian experience of carbon capture and storage in an offshore depleted natural gas field. Focus on monitoring plan activities

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Keywords: carbon capture and storage, monitoring plan, ISPRA.

ISPRA is involved in the permitting process for the geological storage of CO_2 captured from the flue gas of a turbine serving a methane compressor station in Porto Corsini (RA), providing technical and scientific support to the National Secretariat for CCS ("Carbon Capture and Storage")*.*

The first experimental CO_2 geological storage project in Italy was authorized on 26 January 2023 under the simplified procedure set out in Decree No. 162/2011, in line with Directive 2009/31/EC on the geological storage of carbon dioxide. At the time of authorization, this procedure was in force before the enhanced mandatory monitoring actions introduced later by Legislative Decree No. 181 of 9 December 2023.

The project involves capturing CO_2 produced at an onshore plant, transporting it via a 9-km-long sealine to an offshore platform in the Northern Adriatic Sea, and subsequently injecting and permanently storing CO_2 streams in a depleted gas reservoir located 3,000 meters beneath the seabed. This reservoir is characterized by suitable porosity and permeability for CO_2 storage along with a clayey-marly caprock to prevent CO_2 migration.

The experimental program of the Ravenna CCS Hub will involve the injection, which began in August 2024, of a total volume of 50,000 tonnes of CO_2 over a maximum duration of two years (about 25,000 tonnes per year). By 2030, in the full operational phase, the annual CO_2 injection capacity is estimated to be 4 million tonnes per year.

Although a mandatory Monitoring Plan was not required at the time of application and authorization, specific monitoring activities were nevertheless planned for microseismic activity, ground deformation, well and pipeline integrity, and potential environmental impacts.

These were addressed to verify compliance with model outputs and to assess any significant negative effects on the surrounding environment. They also aim to evaluate the effectiveness of any corrective measure of prevention and protection to be taken, both in terms of plant operation and management, and to update the safety and integrity assessment of the storage site. Although potential CO_2 leakages to the surface are considered unlikely, they will be monitored through dedicated well integrity checks and environmental surveillance programs, including detection of anomalies in sediment, water column and marine biota, as required during the technical permitting process assessment.

Submarine cables in the energy transition: ISPRA's role focusing on the marine environmental protection

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Keywords: submarine cable, environmental characterization and monitoring, sensitive and protected marine ecosystem.

All continents are interconnected and interdependent thanks to a complex network of linear infrastructure that crosses the seabed to transport fossil fuels, electricity and communications.

The interconnection via cables or pipelines, while requiring a very high initial investment, enables safe transportation over long distances with an expected low environmental impact and low operating costs. Technological advances and the continued search for innovative solutions for laying such infrastructure, even in extreme conditions, have made it possible to meet the growing demand on a global scale for efficient and continuous transport of both energy and internet data through the marine environment.

This topic is recently gaining importance because of the need to strengthen and implement high-voltage electricity interconnection and the strong drive for energy production from renewable sources which may contribute to energy transition.

ISPRA has been dealing for years with the environmental impacts associated with handling the seabed for the laying of submarine cables. It also provides technical and scientific support to the Ministry of the Environment and Energy Safety to authorize seabed handling for laying submarine cables (Italian Legislative Decree 152/2006, Art. 109). Furthermore, since last year there has been a significant increase in development interventions for the National Transmission Grid together with the launch of countless offshore wind farm projects connected to the mainland by submarine cables.

In this context, ISPRA provides its scientific expertise in compliance with current regulations to ensure the protection of the coastal and marine environment.

The interaction of these activities with the marine environment may cause disturbance to marine ecosystems, depending on how cables are laid and protected, the environmental characteristics and the vulnerability of the area involved. In particular, cable laying can interfere with some protected habitats or species and ecosystems of high naturalistic value (i.e., *Posidonia oceanica* meadows, coralligenous outcrop) due to the routing on the seabed and for handling of seabed associated with the positioning of cables causing habitat fragmentation, increase of turbidity, resuspension of potentially contaminated sediments etc.

The acquisition of an environmental authorization for the construction of submarine cables requires multidisciplinary environmental investigations to be carried out before (characterisation), during and after the laying and protection of the cables (monitoring).

In order to enhance the knowledge and the protection of the marine environment, ISPRA, according to its role, intends to acquire these data, create a cartographic database and make it available to all interested parties.

Multidisciplinary study of nonvolcanic CO_2 degassing in the southern Apennines: definition of the buried reservoirs and seeping mechanisms through geophysical survey

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Keywords: geophysical survey, nonvolcaninc degassing, CO_2 storage.

Understanding the dynamics of natural CO_2 reservoirs and their leakage mechanisms is crucial to support the development of safe and efficient Carbon Capture and Storage (CCS) strategies, contributing directly to the ongoing energy transition towards climate neutrality. In this framework, we present a multidisciplinary investigation focused on two key degassing areas of the southern Apennines: Mefite d'Ansanto and Contursi-Oliveto Citra. These sites, characterized by intense nonvolcanic CO_2 emissions, offer natural laboratories to explore the subsurface architecture controlling gas storage and migration processes.

With over 2000 t/day of CO_2 emissions, Mefite d'Ansanto represents the largest nonvolcanic degassing site in Italy and possibly worldwide. Rising mantle-derived fluids are stored in a shallow carbonate reservoir (500-1000 m depth) partly sealed by a clayey cover and connected to the surface by a complex system of faults and fractures. Despite several studies, critical uncertainties remain regarding the exact reservoir location, its volume, and the structural controls on gas pathways.

To address these questions, advanced geophysical surveys were implemented within the MEFITIS project. In the Mefite d'Ansanto area, a high-resolution 3D Magnetotelluric (MT) survey and a detailed gravimetric campaign were conducted. Over 50 new gravity stations, co-located with AMT soundings and precisely positioned via GNSS RTK, allowed the construction of a Free-Air anomaly map corrected for topographic effects. Residual gravity anomalies revealed a N-S trending dipolar structure (~2 mGal amplitude), with the main degassing area located near the maximal horizontal gradient, highlighting its correlation with a major subsurface fault zone controlling gas migration.

MT surveys further contribute by imaging low-resistivity anomalies linked to gas-saturated formations, allowing the estimation of the reservoir's extent and the identification of key structural traps and leakage pathways. In the Contursi-Oliveto Citra area, a deep 2D MT profile explores the reservoir geometry down to > 5 km depth, integrating geophysical interpretations with observed surface emission anomalies and new gravimetric survey designed accordingly with the MT results.

The integration of gravimetric, MT, geochemical, and structural data will provide critical insights into the storage capacity, containment integrity, and leakage potential of these natural CO_2 systems. These results will offer analog models for future CCS applications, supporting the design of safer and more sustainable subsurface storage solutions essential for the energy transition.

Increasing density of Shallow Geothermal Systems (SGS) and implications for groundwater: unmanaged conflicts and potential synergies

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Keywords: shallow geothermal systems, underground thermal management, thermal interference.

During the last decades, European countries greatly invested to promote renewable energy systems for building conditioning, especially in form of shallow geothermal systems (SGS). These systems allow the efficient exchange of low temperature thermal energy stored in the shallow portion of the subsurface with the building without requiring anomalous temperature gradients (as happens for high enthalpy systems). Switzerland has been a pioneer country for SGS, with decades of investments, research and know-how that led to a wide deployment of this technology; Switzerland now hosts the highest concentration of SGS per km^2 in the world. Especially in urban contexts, new systems are progressively being installed in the proximity of existing ones and interactions could occur, both in terms of negative and positive thermal interferences. This arises some thoughts on the long-term sustainability of such scenario. Is it possible to assess the more frequent interactions between SGS given their increasing proximity and how the current authorization trends could be managed in the near future to ensure a proper thermal management of the groundwater? This work presents the current situation in Switzerland and Canton Ticino with numerical modeling of the urban aquifer of Locarno (Switzerland), simulating mutual interactions between open and closed-loop SGS. Results show that the high amount of installed SGS in limited space is progressively creating mutual hydraulic and thermal interferences: negative, with a reduction of SGS efficiency and sustainability or (rarely) positive, when an accidental and unmanaged synergic effect is established due to favorable exploitation patterns and SGS locations. Moreover, the presence of underground structures affects the thermal conditions of the subsurface and consequently the operation of SGS. Neglecting an underground holistic vision of the hydro/thermogeological processes could result in long-term efficiency losses and thermal issues for SGS solutions, also given the increasing exploitation of shallow geothermal energy for building conditioning.

Deep laser drilling for heat exchangers: the DeepU project concept and results

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Keywords: geothermal energy, laser drilling, deep heat exchangers.

Increasing the accessibility of deep geothermal resources for low-carbon heating and power generation is essential to accelerate the development of decarbonised and indigenous energy supplies in Europe. Advances in technology, particularly deep heat exchangers (DHE), are opening new horizons for geothermal energy, promising to make it an attractive option everywhere, extending beyond the limits of hydrothermal reservoirs. The main advantages of DHE include their versatility, replicability, predictability, low water consumption, and limited development risks related to resource availability. The primary technological challenge arises from the considerable drilling length required to create a sufficient heat transfer area in the subsurface. To overcome this limitation and make DHE projects economically viable, the DeepU technology aims to demonstrate at the lab scale the feasibility of using a combined laser and cryogenic gas drilling action. DeepU stands for "Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation," a European research project launched in 2022 and concluding in 2025. The developed technology aims to optimize the drilling process and reduce costs by increasing penetration rates and productive drilling time while avoiding wear of the drilling head, as it employs a non-contact method. Its laboratory-scale demonstration provides information necessary for assessing technological, environmental, and economic sustainability, as well as defining the potential and commercial attractiveness of the proposed solution.

In the demonstrated DeepU concept, a laser drill head is integrated with specialized drill strings that facilitate the combined action of laser and cryogenic gas, effectively spalling, melting, evaporating, and cooling even the hardest rocks. The fine particles of the drilled rock are expelled to the surface in the gas stream via the borehole annulus. Detailed temperature control analysis and innovative laser lenses are used to convey heat and sustain drilling. The meticulous optimization of laser parameters and experimental setups, along with microscopic examinations of the drilled rocks, has unveiled macro- and micro-scale phenomena that contribute to the successful development of this innovative drilling method. Laboratory tests with the novel lightweight laser and gas processing drill head were conducted within a press container equipped with monitoring devices. Both an optical camera and a thermal camera monitor the process. The interactions between the laser and rock, including thermal spallation, melting, and vaporization, were examined utilizing advanced analytical techniques such as thermography, photogrammetry, and electron microscopy to elucidate the physical nature of the drilling process.

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Crystal structure of new hybrid halide perovskites with sulphonium cation as a key for the ecological transition

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Keywords: organometal halide perovskites, photovoltaic panels, ecological transition.

Organometal halide perovskites (OMHPs) are promising materials for the ecological transition due to their low cost and exceptional optoelectrical properties, being also easily tunable by design and synthesis. Recently, due to the less-defective structure of the perovskite layer, the differing dimensionality of inorganic framework and the high-power conversion efficiency of the resulting photovoltaic panels, a class of OMHPs, in which triphenylsulfonium [$(Ph)_3S^+$] or trimethylsulfonium [$(CH_3)_3S^+$] are chosen as the organic cations, with a lead-halide and bismuth-halide framework, have attracted attention (e.g., Kim et al., 2024). In the present work, we explore in detail the effect of triphenylsulfonium [$(Ph)_3S^+$] substitution on the crystal structure and performance of lead-halide (I, Br, Cl) perovskites. Sulfonium salts are attractive because of the strong charge assisted chalcogen bond at the sulfur center (e.g Kutznetsova et al., 2024). The presence of other substituents, like iodide or thiophenyl groups, as well as the presence of the phenyl group itself, makes these systems potentially highly manageable with a multitude of weak interactions, although the bulky nature of this cation suggests the formation of 0D or 1D perovskites. The fine tuning of the solution synthesis method, confirmed by X-ray diffraction and vibrational spectroscopy (FTIR and Raman spectroscopy) characterization, suggests the presence of at least 8 new perovskites-like samples. Crystals were prepared by three different solution synthesis methods (direct precipitation in water at cold temperature, highly volatile polar organic solvent and using dimethylformamide - DMF - as evaporating solvent), that lead to different crystal structures. The crystal structure characterization of three OMHPs, that is, $(Ph)_3S(PbBr_3)$ (I2/a space group), $(Ph)_3S[PbBr_3(DMF)]$ ($P2_1/n$ space group) and $(Ph)_3S[PbI_3(DMF)]$ ($P2_1/n$ space group) (DMF: N, N'-dimethylformamide), was performed, unveiling 0D and 1D perovskite structures. Vibrational spectroscopy confirms the crystal structures, while UV-vis spectroscopy was used to characterize the band gap. Finally, calculations have been performed for the vibrational assignation and the electronic properties (band gap calculation and PDOS). Further studies are in progress to analyze the mineral physics of the synthesized samples, as well as of different OMHPs (sulfones and iodones with different substituents, thus moving from lead to bismuth and copper), at high pressure and high temperature conditions. This will also allow to check the likely memory effect during decompression, as well as to explore the possible evolution of the electric and conductive properties of this class of materials with pressure and temperature.

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Exploring cave systems as natural analogues for studying CO_2 leakage risk

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Keywords: carbon dioxide, karst critical zone, cave monitoring.

The investigation of the potential risk associated to gas leakage in geological carbon storage sites (CCS) is a crucial challenge for preventing environmental impacts on ecosystems and to ensure an agile approach towards the sustainable energy transition prospected for the near future. Karst systems are the expression of the high secondary porosity in heterogeneous carbonates and represent useful natural analogues where investigate how carbon dioxide (CO_2) is transported within the Earth's critical zone.

This study explores the natural CO_2 emissions in a karst vadose zone in NW Sardinia (Italy) with the aim to provide a surrogate of the geological sequestration sites for the investigation of the behaviour of gas leakage and for its early detection at the surface. For this purpose, standard micrometeorological techniques have been applied in a 100 m-deep shaft (where high CO_2 concentration was previously detected) in order to investigate the gas permeable structure of the karst critical zone and to identify the carbon flux at the geosphere-atmosphere interface. The cave atmosphere was examined at -10 m-deep from the entrance with multiple meteorological sensors that recorded continuously air CO_2 and other micrometeorological parameters (temperature, relative humidity, barometric pressure, direction and intensity of cave air masses movement).

The cave atmosphere monitoring, adapted to site-specific conditions, has shown that the temporal variation in gas concentration can be explained by advection/convection processes related to atmospheric variables. The barometric pressure pumping and, with minor contribution, the thermal instability have been recognized as the main drivers in the upwards migration of substantial amounts of CO_2. During the year, fluctuations in barometric pressure drove the advective transport of CO_2 from the deep vadose zone to the atmosphere on a semi-daily time scale, while the seasonal variability in atmospheric temperature led to phases of thermal instability, more frequent in winter rather than in summer. The results also suggest that near-surface measurements inside caves could help in developing, testing and optimizing different monitoring platforms, also equipped with low-cost probes, capable of detecting gas emissions even at concentration close to atmospheric values.

Reusing depleted oil and gas wells for geothermal heat production in Italy

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Keywords: geothermal energy, hydrocarbon well, geothermal repurposing.

Climate change and the ongoing energy crisis are driving industrialized countries to reduce CO_2 emissions and increasingly rely on domestic renewable energy sources. Among these, geothermal energy holds significant potential, particularly considering that space heating and cooling accounted for 48% of final energy consumption in the EU20 countries in 2021.

Many depleted oil and gas reservoirs have sufficiently high temperatures to enable geothermal energy extraction. Consequently, wells located in hydrocarbon fields with geothermal potential could be repurposed for geothermal use as they approach the end of their productive life. This conversion represents a viable alternative to well abandonment, which would otherwise preclude any future geothermal reuse. Such an approach aligns with circular economy principles and supports the decarbonization of energy production. Moreover, repurposing existing hydrocarbon wells significantly reduces the risks and costs typically associated with drilling new geothermal wells.

Available data indicate that Italy has more than 1,500 active hydrocarbon wells, with different operational status, around 840 of which are located in onshore concessions. As many of these wells near the end of their productive life, a systematic assessment of their geothermal potential is necessary before permanent closure. To this end, a national screening has been conducted using a simplified methodology to compare well locations with subsurface temperature data (e.g., Alimonti et al., 2021), focusing specifically on onshore wells classified as productive or potentially productive.

Several possible technologies have been proposed to harvest the geothermal heat from mature hydrocarbon fields, including: 1) co-production of residual hydrocarbons alongside hot formation water, 2) open-loop systems developed reconfiguring existing wells to operate as paired injectors and producers, and 3) closed-loop system involving the installation of borehole heat exchangers in existing wells or connecting existing well with newly drilled lateral well segments. These approaches vary in terms of the required level of intervention - from utilizing wells in their current configuration to performing extensive workovers, or even drilling new wells.

In our study, we explore the advantages and limitations of these different technological solutions through a series of case studies in Italy (e.g., Soldo et al., 2020; Alimonti et al., 2024). Although the temperature profiles of the Italian onshore depleted hydrocarbon wells are generally in the medium-to-low range, due to their location in sedimentary basins with relatively low heat flow, our analysis and case studies demonstrate that a significant number of them can be repurposed using existing technologies. These wells could supply fluids at suitable temperatures for various direct-use applications, including district heating.

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Advancements in the development of novel laser drilling technology for geothermal energy exploitation (DeepU)

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Keywords: geothermal energy, laser drilling.

Increasing the accessibility of deep geothermal resources for low-carbon heating and power generation is essential to accelerate the development of decarbonised and indigenous energy supplies in Europe. Geothermal technologies offer baseload, indigenous, and dispatchable renewable power and heat for space heating and industrial applications. Advances in technology, particularly deep heat exchangers (DHE), are opening new horizons for geothermal energy, promising to make it an attractive option everywhere, extending beyond the limits of hydrothermal reservoirs. The main advantages of DHE include their versatility, replicability, predictability, low water consumption, and limited development risks related to resource availability. The primary technological challenge arises from the considerable drilling length required to create a sufficient heat transfer area in the subsurface. To overcome this limitation and make DHE projects economically viable, the DeepU technology aims to demonstrate at the lab scale the feasibility of using a combined laser and cryogenic gas drilling action. DeepU stands for "Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation," a European research project launched in 2022 and concluding in 2025. The developed technology aims to optimize the drilling process and reduce costs by increasing penetration rates and productive drilling time while avoiding wear of the drilling head, as it employs a non-contact method. Its laboratory-scale demonstration provides information necessary for assessing technological, environmental, and economic sustainability, as well as defining the potential and commercial attractiveness of the proposed solution.

In the demonstrated DeepU concept, a laser drill head is integrated with specialized drill strings that facilitate the combined action of laser and cryogenic gas, effectively spalling, melting, evaporating, and cooling even the hardest rocks. The fine particles of the drilled rock are expelled to the surface in the gas stream via the borehole annulus. Detailed temperature control analysis and innovative laser lenses are used to convey heat and sustain drilling. The meticulous optimization of laser parameters and experimental setups, along with microscopic examinations of the drilled rocks, has unveiled macro- and micro-scale phenomena that contribute to the successful development of this innovative drilling method. Laboratory tests with the novel lightweight laser and gas processing drill head were conducted within a press container equipped with monitoring devices. The interactions between the laser and rock, including thermal spallation (Kant et al., 2017), melting, and vaporization (Feng et al., 2025), were examined utilizing advanced analytical techniques such as thermography, photogrammetry, and electron microscopy to elucidate the physical nature of the drilling process.

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Effects of bioturbation on porosity and permeability in shallow-water carbonates: a case study from the Appenine Carbonate Platform (Italy)

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Keywords: bioturbation, carbonate rocks, petrophysical properties.

Bioturbated carbonate sequences pose significant challenges for reservoir characterization in both hydrocarbon exploration, exploitation and underground CO_2 storage. Bioturbation can strongly influence the petrophysical properties of host rocks, generating sedimentary heterogeneities and often modifying the original porosity and permeability. This study investigates a 75-meter-thick Upper Cenomanian–Lower Turonian bioturbated carbonate succession from the Apennine Carbonate Platform in Southern Italy.

A comprehensive, multidisciplinary approach was employed, integrating facies, ichnological and petrophysical analyses, supported by non-destructive imaging techniques such as CT and Micro-CT scanning. Porosity was measured using mercury intrusion and resaturation methods, while permeability data were obtained using a probe permeameter and through software-based simulations, allowing for direct comparison between burrow structures and the surrounding matrix. To evaluate rock-fluid interactions under CO_2-rich conditions, batch experiments were also conducted on selected samples. CT imaging was used to quantify burrow geometry, connectivity, and tortuosity, assessing their influence on fluid flow properties. High-resolution Micro-CT data enabled detailed modelling of porosity and permeability, which was subsequently cross-validated against the laboratory results.

The examined sequence exhibits a boxwork pattern of burrows organized with a preferential horizontal network featuring vertical shafts exhibiting Y- or T-shaped morphologies typical of the *Thalassinoides* ichnotaxa. Bioturbation intensity and porosity increase upwards in the section. CT imaging reveals low-tortuosity burrow pathways with circular to elliptical cross-sections. In the most bioturbated intervals, burrows occupy approximately 39% of the rock volume and are predominantly dolomitized, with porosity ranging from 1.8% to 17.7%. In contrast, matrix porosity ranges from 1% to 4.8%. Permeability measured values (~101.8 mD) are consistent with those modelled from micro-CT-based simulations (~117 mD).

The findings of this study emphasize the substantial impact of bioturbation on the distribution and quality of porosity and permeability in complex carbonate reservoirs providing valuable implications for understanding fluid migration, rock-fluid interactions, and diagenetic processes.

Terrestrial heat flow, a baseline for the evaluation of geothermal potential: current knowledge in Italy and surrounding seas

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Keywords: heat flow, geothermal database, renewable energies.

Terrestrial heat flow is the primary geophysical parameter to understand the thermodynamic conditions within the Earth's interior. Variations in heat flow provide fundamental insights into the thermal regime and, coupled with other geodata, contribute to our understanding of large-scale geodynamic processes, fluid flow and the distribution of geothermal resources. Heat flow values are systematically determined in continental and marine settings with different techniques (scientific and industrial drilling, mine tunnels, oceanic probes, etc.) and accuracy. An updated, referenced, quality-checked heat-flow database is fundamental to defining the spatial distribution of geothermal resources and their possible use in conventional processes (e.g., electricity generation, heat direct uses) or new technologies (retrofitting of oil wells, brine mining, borehole heat exchangers).

The Global Heat-Flow Database (GHFD), managed by the International Heat Flow Commission (IHFC), is the only fully referenced data source, continuously updated since 1963. In 2020, the IHFC initiated a fundamental project to revise the GHFD structure. The process involves a multi-national collaboration, also in synergy with the International Lithosphere Program. The new database is structured to contain appropriate metadata documentation to control the quality of the heat-flow values.

Since the launch of the IHFC project, we have been working on revising thermal data collected in Central-Southern Europe, North Africa, and the Middle East. Over the past four years, we have predominantly focused on the heat-flow data from the Italian peninsula and the surrounding seas. This paper presents the current status of available continental and marine heat-flow data, primarily sourced from the GHFD and partially still under revision.

Considerable progress has been made since the early heat-flow compilations and mappings of the 1970s. Currently, there are over 900 available heat-flow sites in the Italian peninsula and surrounding seas, in contrast to the approximately 50 determinations reported in the first published compilation.

Most determinations (more than 650 heat flow sites) have been collected at sea (Tyrrhenian Sea, the Ligurian-Provencal Basin, the Sardinia and Sicily channels, the Adriatic and the Ionian seas). The largest variability in heat flow characterises the Tyrrhenian basin, and values up to about 900 mW m-2 can be observed. The lowest values were observed in the Adriatic Sea.

Onshore, the current heat-flow dataset generally supports the initial findings of earlier studies, indicating a significant decrease eastward across the peninsula, both in the north and south sectors. However, the ongoing revision of the heat-flow database is expected to improve our understanding of local thermal patterns, thereby providing effective support in mapping the potential for geothermal energy production and storage at various scales.

Preliminary estimation of the shallow geothermal energy potential based on comparison of thermal properties and hydrogeochemical parameters: insights from the Sibari Coastal Plain (Calabria, Southern Italy)

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Keywords: Sibari Coastal Plain, groundwater, geothermal energy.

The PNRR 2023-2026 Tech4You project aims to provide a robust assessment of the geothermal potential of the Sibari Plain for the deployment of ground-source heat exchangers (GSHEs) and groundwater heat exchangers (GWHEs) for indoor heating and cooling, while also accounting for potential geochemical issues associated with the intensive use of open-loop systems (Vespasiano et al., 2023). Thermal, geological, and hydrogeological data have been compiled and processed using the methods of Casasso & Sethi (2016) for closed-loop systems (G.POT) and Muñoz et al. (2015) for open-loop configurations. Preliminary results indicate that the central-eastern sector of the plain is the most suitable area for geothermal uses, because high soil permeability and a shallow water table enhance the subsoil's heat exchange capacity. However, the direct use of groundwater through open-loop systems necessitates a thorough evaluation of possible geochemical and microbiological issues. In this context, the analysis of groundwater chemistry enables the identification of the corrosion and scaling potentials. The outcomes of this research will support the planning of small-scale GSHEs and GWHE installations, fostering environmentally sustainable heating and cooling technologies, reducing greenhouse gas emissions, and providing cost-effective alternatives to conventional HVAC (Heating, Ventilation, and Air Conditioning) systems. Moreover, addressing critical geochemical challenges will contribute to developing effective regulatory frameworks for resource management and geothermal concession policies.

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Analysis of deep carbonate platform deposits for the evaluation of geothermal potential assessment in the Valle Latina (Central Apennine, Italy)

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Keywords: geothermal potential assessment, Valle Latina, structural geology.

Geothermal energy is a significant resource, and effectively harnessing it requires the identification of deep geothermal systems, which include the heat source, reservoir, and transport medium—typically water in its various phases, depending on the temperature and pressure.

This work focuses on the geothermal potential of the southern Latium region, which has been relatively underexplored in the past for geothermal energy. In recent decades, studies have focused on defining the buried carbonate structures and their structural trends, particularly in the Valle Latina area, to characterise potential carbonate reservoirs, having a main secondary porosity due to their extensive network of fractures. The top of a Miocene-Cretaceous carbonate platform was identified as the main regional seismic reflector, a key element for interpreting the carbonate reservoir along the subsurface seismic reflection data. The outcomes suggest a possible hybrid tectonic style for the Valle Latina, indicating a transition from the dominant thrust tectonics (active for most of the structuring of the orogen) to an extensional deformation (limited to the last 3 Ma). During the Tortonian period, pelagic deposits of the Frosinone Formation were compressed and pushed onto the carbonate platform domain deposits, serving as a seal in the investigated geothermal system. Thanks to the new digitalized and vectorized dataset and the application of seismic attributes analysis, it has been possible to achieve a better definition and interpretation of the interface between Upper Miocene siliciclastic deposits and Mio-Cretaceous carbonates in the area of study, characterized by strong acoustic impedance contrast. The current study employs a multidisciplinary approach to assess the selected area's geothermal potential by defining the carbonate reservoir's structural setting and its temperature at depth. Some of the most promising carbonate structures have been selected, and the volume method has been applied to assess their geothermal potential. A probabilistic approach has been used to evaluate the "Farnese" prospect, aiming to provide a distribution of technical potential rather than a single value. The results indicate that there is a significant amount of heat available, both in the low-to-mid-enthalpy range and in the high-enthalpy range. To gain a clearer understanding of how existing wasted heat can be utilized, it is essential to assess the production capabilities of other structures and the surrounding areas.

Geological characterization of potential geothermal reservoirs in complex basin systems: a study case in the Tertiary Piedmont Basin, NW Italy

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Keywords: tertiary Piedmont basin, geothermal reservoirs, basin analysis.

The exploration of potential geothermal resources in complex basins, such as piggyback or wedge-top basins, requires the integration of geological and geophysical studies to constrain the lithology and architecture of potential reservoir units, to understand possible fluid flow paths and to infer possible heating mechanisms in the basins. This study focuses on the characterisation of the fractured crystalline basement rocks, likely acting as a reservoir, and the above sedimentary cover of the Tertiary Piedmont Basin (TPB) in north-western Italy. The TPB consists of a thick sequence (up to ca. 6 km) of tectonically controlled sedimentary deposits, Eocene to Pliocene in age, overlying the metamorphic units of the Ligurian and Western Alps to the west and the Inner and Outer Ligurian units to the east. The dynamic tectonic framework of the region has caused continuous and progressive deformation of the basement and its covers, promoting complex fracture patterns in the basement and the development of kilometre-wide structures that control the basin architecture (Maino et al., 2013). Evidence for geothermal activity in the basin includes surface heat fluxes between 62 and 84 mW m^{-2} (Pasquale et al., 2014), the presence of active thermal springs (e.g., La Bollente and Lago delle Sorgenti in Acqui Terme), and locally high geothermal gradients (70 to 90 mKm^{-1}, Pasquale et al., 2011), in the southern part of the basin, where fluid circulation and heating within the fractured Alpine basement is most likely to occur. We show results obtained from the integrated analysis of geological/geophysical data to characterise and classify possible reservoir and seal units in the TPB succession. A 3D model was implemented, based on a merged geologic map of the area and the interpretation of seismic reflection lines, which show the geometry (e.g. thickness and depth) and spatial distribution of basement and sedimentary cover. Field observations, present brittle structures, and the behaviour of hydrothermal systems in the area point out the basement units as the main geothermal reservoir, in agreement with the study of Pasquale et al. (2011). To characterize this metamorphic reservoir, the rocks of the Ligurian Alps, including the Voltri and Valosio groups and Voltaggio units, were studied using field structural analysis, Digital Outcrop Model mapping, and fracture intensity analysis coupled with petrophysical data. The sedimentary cover sequences were classified as seal units or secondary reservoirs through the analysis of sedimentary facies, grain size ratios, and petrophysical data from available well logs.

The analysis of the potential reservoir and seal units allowed to provide a preliminary assessment of the geothermal potential system in the TPB, representing a solid starting point for developing a more detailed geothermal resources evaluation.

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Paving natural hydrogen geology: the contribution of metamorphic petrology and geochemistry

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Keywords: natural hydrogen.

Molecular hydrogen research has gain international interest for its potential applications in the energy transition. Compared to industrial H_2, production cost of which remains high, natural molecular hydrogen, or "natural hydrogen", is produced by nature in amounts that may potentially satisfy global demand for good. Nevertheless, natural hydrogen formation, migration, and accumulation in the crust remain largely unknown to the scientific community, as well as the possibility for this molecule to reach the near subsurface and to accumulate over sufficient timescales. The aim of this contribution is to present examples of the contribution of the metamorphic petrological and geochemical approach on the understanding of natural hydrogen formation and fluxes, migration, and reactivity with common continental crustal rocks. From the Alpine belt back to the Precambrian, results from four case studies will be presented to illustrate how, in this critical step of natural hydrogen exploration, metamorphic petrology and geochemistry provide fundamental insights on the formation, migration, and accumulation of natural hydrogen.

The role of fracture analysis in geothermal areas: the HOCLOOP project

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Keywords: fracture network, geothermal reservoir, hocloop project.

Understanding of the thermal role of fracture networks is one of the objectives of the HOCLOOP (HOrizontal Closed LOOP) project, which involves the study of a horizontal well in which a fluid (water or CO_2-based fluid) circulates in a closed system characterised by an inner and an outer pipe, the latter in contact with the rock. The interaction between heat transfer and fracture systems is poorly understood in closed-loop heat mining, which tends to focus on the thermal properties of the host lithology, despite its importance for mining efficiency and risks.

Three pilot sites located in Italy were selected for simulation of heat extraction, based on their different rock composition, thermal gradient and assumption of mining heat at a depth of about 1 km. In each area, representative outcrops were selected to study fracture frequency and connectivity. These areas are located in Tuscany (Mt. Amiata and Gavorrano areas), where the heat flow shows an anomaly with an average value of about 120 mW/m^2 and a local peak of up to 1000 mW/m^2 corresponding to the Larderello geothermal area, and in Puglia (Manfredonia, Gargano promontory), where the heat flow is of about 40 mW/m^2. In particular, the Mt. Amiata volcano-geothermal area is characterised by a heat flow of about 80 mW/m^2, with peaks of up to 600 mW/m^2. The heat is due to the cooling of a magmatic body (0.3-1.9 Ma), emplaced at 6-8 km depth, driving hydrothermal mineralisation, travertine deposition (ongoing), thermal springs and gas vents. The Gavorrano area is characterised by a heat flow of about 70 mW/m^2. A Neogene (4.9 Ma) monzogranite body, emplaced at 2-2.5 km depth, produced a widespread circulation of geothermal fluids, resulting in an extensive Fe-ore (mainly pyrite) deposit, which was exploited during the last century. The Gargano area (Puglia) is characterised by a heat flow of about 40 mW/m^2. This area consists of a 3-4 km thick succession of carbonate rocks (Jurassic-Eocene), locally well exposed in road cuts or quarries and affected by several faults.

This study will allow to better define the fracture network of each site and to develop different scenarios to simulate the heat extraction, contributing to the evaluation of the thermal energy exchange between the geothermal reservoir and the working fluid (water or supercritical CO_2), and the cooling of the reservoir over time.

In order to do so, based on an existing thermodynamic model of the well, which also takes into account the possible presence of a convective flow in the reservoir that enhances the heat transfer between the well and the surroundings, an advanced statistical approach has been developed to assess the probability of obtaining an increase in the power output of the well itself, given the statistical distribution of fractures measured in the field and the uncertainty in the presence and in the strength of a convective fluid.

S22.

Hydrogeology and geochemistry of mineral and thermal waters

Conveners and Chairpersons

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Marco Pola (Croatian Geological Survey, Zagreb, Croatia)

Integrated morphometric and geological analysis for the identification of thermal water recharge area: the case of Acquasanta Terme (Central Apennines)

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Keywords: Acquasanta Terme, geothermal system, recharge area.

The Acquasanta Terme anticline, located in the Central Apennines, is an east-vergent structure of about 30 km in extension with a N-S direction at the centre of which, near the town of Acquasanta Terme, sulphate-chlorinated thermal waters with a temperature above 30°C come to light (Boni et al., 1986). The outcropping rock formations relate to the Meso-Cenozoic Umbria-Marche succession, of which only the units starting from the Scaglia Rossa up to the extensive siliciclastic sediments of the Laga Formation are included. There are also large travertine deposits on the right bank of the Tronto River, which result from the action of the thermal waters. The thermal water sources are fed by a geothermal system whose waters are of meteoric origin (Fusari et al., 2017), which once infiltrated into the underground flow inside the Calcare Massiccio formation, in contact with the Burano Anhydrites. The geothermal gradient (22°C/Km) represents the heat source. Two hypotheses have been proposed regarding the recharge area of the Acquasanta Terme geothermal system: Menichetti (2008) proposed the Sibillini Mountains as a recharge area, while Fusari et al. (2017) proposed the Laga Mountains. In agreement with the latter, the meteoric water infiltrates in an altimetric range between 1500 and 1700 m a.s.l. This study aims to identify the hydrogeological basin of the geothermal system of Acquasanta Terme with particular focus on the location of the recharge area. A morphostructural analysis was done in the surrounding area, including the Laga Mts., Mount Vettore massif and Gemelli Mountains, where the territory is between 1500 and 1700 m in altitude. This characterisation, based on DEM, is morphometric and hydrological, thus allowing the territory to be characterised regarding rainwater infiltrations. These analyses were integrated with geological analyses to characterise the deep structure of this portion of the Apennine and to define possible water paths within the calcareous formations. Two orthogonal geological crosscut sections were created, one N-S from the Laga Mts. to the town of Acquasanta Terme and the other W-E from the Sibillini Mts. to the town.

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Multidisciplinary investigations for the conceptual modeling of hydrothermal systems in northern Croatia: the HyTheC project

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Keywords: thermal water, carbonate reservoir, northern Croatia.

Northern Croatia is characterized by several thermal springs (temperatures up to 65°C) in approximately 20 localities (Borović & Marković, 2015). These thermal waters are mostly used for recreational and balneological purposes, but they represent strategic natural and economic resources for the future green transition in Croatia.

The springs are the outflow of intermediate scale, topographically driven, hydrothermal systems with similar geological properties. The thermal waters are of meteoric origin with the recharge areas located in the mountainous hinterlands of the springs. The infiltrated waters flow through a Mesozoic carbonate reservoir and are heated by an above-average heat flow, which results from the peculiar thermal setting of the southern Pannonian basin (Horváth et al., 2015; Macenić et al., 2020). The discharge of the thermal waters is promoted by an increased fracturing and permeability field of the bedrock resulting from the local structural setting. The HyTheC project promotes a multidisciplinary approach for investigating hydrothermal systems that integrates structural geological, hydrogeological, geothermal, hydrogeochemical, geophysical, and remote sensing investigations. The project results were used to: 1) propose a conceptual model of the system, 2) perform a 3D geological model of the studied area, 3) assess the hydrogeological and thermal properties of the main hydrostratigraphic units, and 4) conduct numerical simulations of the system functioning.

The methodology was tested in three pilot hydrothermal systems with different degrees of previous knowledge. The Daruvar system was the most investigated with a recent conceptual model corroborated by 2D numerical simulations. HyTheC detailed the regional and local structural settings, which favor the thermal water flow, and quantified the impact of geological and physico-chemical processes on the development of the system through 3D numerical simulations. The Topusko system was previously poorly investigated, while the recharge area was not determined. The multidisciplinary approach focused on hydrochemical and hydrogeological characterizations, the development of a conceptual model and its physical validation through 2D numerical simulations. The Hrvatsko zagorje system is the largest one, with a diffuse outflow of thermal water. A 3D regional geological reconstruction of the study area was conducted, while numerical simulations of fluid flow and heat transport are under development.

The results of the HyTheC project highlight the importance of conducting multidisciplinary investigations for the characterization of hydrothermal systems. The obtained results will serve to protect these resources complying with many European and national strategic documents, regulating energetics, tourism, and environmental protection.

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The current situation of the Euganean geothermal fields: challenges and opportunities for sustainable development

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Keywords: Euganean geothermal field, monitoring network, Veneto region.

The Euganean Geothermal Fields (EuGFs), located in the Veneto region of northern Italy, are among the most significant thermal areas in Europe, renowned for their rich geothermal resources and therapeutic properties. Over the centuries, the area has developed into a key destination for wellness tourism, with almost ninety currently active spas and wellness centers built around its thermal waters. However, the current situation of the EuGFs presents a mix of challenges and opportunities that requires urgent attention from both environmental and economic perspectives.

While the thermal fields remain a key driver of the local economy, their management and the exploitation of thermal waters (15x106 m^3 is the average annual exploitation) face increasing scrutiny due to rising concerns over resource management and the potential effects of overexploitation on the local ecosystem. Furthermore, the recent growing interest in geothermal resources has led to a rising demand for thermal water. In this context, an adequate monitoring network strategy will be essential. The EuGFs have been monitored since the early 1970s, but the renewed interest in geothermal resources necessitates a rethinking of the monitoring network in light of the region's new energy priorities.

A new basic monitoring network for potentiometric levels and temperatures has been designed and is currently in the installation phase. As new projects for the energy exploitation of thermal resources are approved, this basic monitoring network will be expanded to allow more comprehensive monitoring of the induced impacts of this increased exploitation on the EuGFs.

The goal of this approach is to preserve the sustainability of the Euganean Geothermal Fields, ensuring the longevity of geothermal resources while fostering socio-economic development and preserving the region's unique natural heritage.

Thermal logs in the Euganean Geothermal Field (EuGF) in NE Italy

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Keywords: geothermal field, thermal water, thermal logs.

The Euganean Geothermal Field (EuGF) is one of the most significant geothermal areas in Italy, located in the Veneto region, in the province of Padua (NE Italy). It is characterized by a water-dominated, low-enthalpy geothermal resource, with temperatures reaching approximately 87°C. The presence of this resource is closely linked to a dense network of fractures associated with regional fault zones (Schio-Vicenza Fault System) and a relay ramp that enhances the regional to local flow of thermal waters. Their rapid upwelling in the Euganean Geothermal Field is facilitated by open extensional fractures deforming the relay ramp (Pola et al., 2020). The thermal waters are hosted in a carbonatic fissured reservoir located beneath approximately 100 to 200 meters of alluvial sediments.

Euganean thermal fluids have been known since Roman times for both recreational and therapeutic purposes. However, the intensive use of this resource in the last century has necessitated continuous monitoring to ensure its preservation. Since the 1970s, a long-term monitoring network has been in place, supplemented over the years by numerous thermal logs campaigns (Fabbri et al., 2017). The first series of thermal logs was conducted between the 1980s and 1990s, followed by a subsequent campaign between 2014 and 2016, totaling about 60 thermal logs. These thermal logs have proven to be a valuable tool for understanding subsurface thermal behavior and for constructing the conceptual model of the geothermal field, providing useful information about the resource reservoir. The historical thermal logs were reanalyzed as part of the TREASURE project in 2025, which aims to implement a new monitoring network in the EuGF. The findings derived from the interpretation of these logs are presented in this contribution.

The analysis shows that the geothermal reservoir is located at varying depths, influencing subsurface temperature gradients, which are not homogeneous across the area. Temperatures gradually increase until they reach the reservoir, where they stabilize, although significant temperature differences can still be observed depending on the well locations. Notable discrepancies in thermal log results are observed between the alluvial cover and the underlying bedrock. Within the alluvial cover, the presence of two sandy aquifers influences temperature trends. In contrast, within the reservoir, the higher hydraulic conductivity of certain zones (Fabbri, 1997) enhances the development of convective flows, promoting temperature homogenization and reducing the thermal gradient. Additionally, the study revealed that the temperatures of the thermal system have not significantly changed over time.

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Groundwater monitoring network in the Cuneo mountain area (Piedmont, Italy): a proposal for integration with mineral water springs used for bottling

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Keywords: mineral water springs, groundwater monitoring network, Piedmont.

In the Alpine context, groundwater plays a crucial role in providing freshwater resources, maintaining ecological balance and supporting biodiversity. A significant portion of freshwater supply in these areas comes from springs, underscoring their importance for both human use and ecosystem health. Consequently, monitoring networks are essential for evaluating the quantity and quality of spring water, especially in the face of climate change. In response to repeated droughts, monitoring is essential to assess groundwater resources. These infrastructures are vital to ensure long-term data collection.

In Cuneo Province, 53% of drinking water comes from mountain springs. However, the current monitoring network in the Cuneo mountain area includes only 4 monitored springs.

From a hydrogeological point of view, the area is characterized by several distinct hydrogeological complexes. The most significant formations, in terms of both the number of springs and their flow rates, include quaternary deposits and fractured rocks complexes.

These hydrogeological settings have given rise to approximately 1,400 springs, many of which are used for drinking water supply, and are not subject to natural flow monitoring.

The relevant availability of groundwater has led to the development of significant mineral water bottling facilities. As a result, numerous mineral springs in the area are subject to continuous monitoring of both quantitative and qualitative parameters (such as flow rate, temperature, electrolytic conductivity), in compliance with European national legislation, the competent regional authority provides for the integration of the monitoring system, if necessary, in implementation of EU directives such as Directive 2000/60/EC of the European Parliament, and as indicated in the Piano di Tutela delle Acque (Water Protection Plan - 2021 update) of the Piedmont Region.

In collaboration with the Piedmont Region, which holds regulatory oversight of bottling companies, the integration of selected springs under mining concession into the groundwater monitoring network was deemed technically feasible. Seven springs were selected for integration based on criteria including spatial distribution, as well as the reliability and consistency of data obtained from previous monitoring campaigns.

The integration of these monitoring points into the regional monitoring network could offer several advantages, both in terms of resource management and cost-efficiency. This extension represents a replicable model that could be adopted in other Italian regions where groundwater monitoring points are currently limited. In some cases, technical adaptations or infrastructure upgrades may be required, which should be planned in close collaboration with facility managers and relevant stakeholders.

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Integrated geological, hydrogeological, hydrogeochemical and isotopic approach for groundwater prospecting in volcanic aquifers

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Keywords: integrated approach, hydrogeology, geochemistry.

A multidisciplinary approach integrating geological, hydrogeological, geochemical, and isotopic investigations was applied to the study of a volcanic aquifer system with the objective of evaluating the potential for identifying groundwater resources suitable for human consumption. The methodology involved the collection and analysis of precipitation and groundwater samples over a defined monitoring period. Precipitation was used to establish a provisional Local Meteoric Water Line (LMWL), which served as a reference framework for interpreting the isotopic composition of groundwater and understanding recharge dynamics.

Stable isotope analyses of groundwater, sampled from both springs and wells, revealed limited variability and showed alignment with the LMWL, suggesting minimal secondary processes such as evaporation or isotopic exchange with aquifer materials. This consistency indicates recharge primarily from direct infiltration of meteoric water, with no significant alteration along the flow path. The stability of isotopic signatures across multiple sampling campaigns, including historical data, further supports the persistence of a stable recharge regime. Geochemical characterization included major ion composition, pH, redox conditions, and selected tracers. Waters generally displayed oxidizing conditions and pH values ranging from slightly acidic to alkaline. Conductivity values were low to moderate and consistent with fresh water systems. Nutrient concentrations, including nitrate and phosphate, were within acceptable limits, with few localized anomalies. The data overall point to groundwater of good quality, suitable for human consumption. Hydrochemical facies were identified using classification diagrams and molar ratios, which revealed compositional differences among the sampled waters. These differences are interpreted as the result of variable residence times, flow paths, and degrees of interaction with the geological matrix. Multivariate statistical analysis, including compositional biplots, was used to explore patterns and relationships among major ions. The results confirmed the presence of distinct groups of waters, corresponding to different recharge areas and degrees of geochemical evolution.

In conclusion, the combined use of hydrogeochemical and isotopic tools provided a detailed understanding of groundwater origin, recharge mechanisms, and subsurface flow processes in a volcanic aquifer. The methodology proved effective for delineating areas of interest and supports the potential for identifying and managing groundwater resources intended for human consumption in complex geological environments. This approach may be replicated in similar volcanic contexts to support sustainable water resource development.

Temporal evolution and characteristics of water isotopes in different thermal and mineral springs in Italy

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Keywords: farfa river, geochemistry, groundwater-surface water interaction.

Water isotopes are used as tracers in the most varied ways and for different practical applications in the study and management of groundwater and springs (definition of recharge areas, pollution, mixing, salt intrusion, etc.).

In this study, data relating to deuterium and oxygen18 were analyzed from about fifteen different Italian locations where thermo-mineral springs are present, together with rainwater and in some cases surface water with which these springs interact. The temporal evolution of both isotopes was evaluated for the period from 2018 to 2022, allowing to distinguish the different characteristics of these waters and the processes (natural and possibly anthropic) eventually in progress.

Spatial distribution of probable arsenic exceedance of natural background levels in Calabria (Southern Italy): a non-parametric geostatistical approach

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Keywords: arsenic, aquifer-based NBLs, probability kriging.

The concept of Natural Background Level (NBL) serves as a key tool in groundwater protection and management, aiming to distinguish between natural and anthropogenic sources of specific contaminants. Traditionally, NBL is defined as a single representative value across large regions, even when the underlying hydrogeological and geochemical conditions vary significantly. However, such an approach may oversimplify the natural variability of contaminant concentrations, which are often influenced by complex and spatially variable hydrogeochemical processes. This is particularly true for arsenic in the Calabria region, where arsenic concentrations show notable heterogeneity, with values varying between a few to more than 400 µg/L. The highest concentrations pertain to shallow groundwaters circulating in a restricted area of the Calabria region, representing an unexplored mineralized spot, making the uniform NBL value even less representative at a local scale (Apollaro et al., 2022).

To address the limitations of conventional NBL assessments and to better reflect the inherent spatial variability of natural arsenic levels, this study proposes an integrated probabilistic approach. This method combines aquifer-based selection criteria with multivariate non-parametric geostatistics to account for hydrogeological and geochemical diversity. Specifically, distinct NBL values were determined according to different aquifer types and relevant hydrogeochemical characteristics. These differentiated NBL values were then incorporated into Probability Kriging to generate spatial maps of exceedance probability, thereby offering valuable tools for contamination risk assessment and management. To further emphasize the effectiveness of the proposed approach, its results were compared with the ones obtained through the more traditional approach (i.e., Indicator Kriging), based on a single NBL value for the entire regional territory.

By integrating the physico-chemical variables used in defining aquifer-specific NBLs, this multivariate geostatistical method enables a physically-based mapping of arsenic exceedance probabilities. Importantly, the approach explicitly incorporates the hydrogeochemical complexity of the study area, including the multitude of processes influencing arsenic distribution in groundwater systems. In addition to be more physically-based, the use of aquifer-based NBL values in the Probability Kriging allowed obtaining improved model performance metrics and less "noisy" mapping, because the natural hydrogeochemical features of each group of waters were filtered out. Consequently, resulting maps of NBL exceedance probability serve as practical tools for contamination risk management to identify areas where the anthropogenic contribution may be relevant and that require further investigation and targeted mitigation endeavors.

Apollaro C. et al. (2022) - A multivariate non-parametric approach for estimating probability of exceeding the local natural background level of arsenic in the aquifers of Calabria region (Southern Italy). Sci. Total Environ., 806, 150345, https://doi.org/10.1016/j.scitotenv.2021.150345.

Hydrodynamic and hydrochemical effects of the upwelling of mineralized connate waters within alluvial aquifers: case study in the Vomano alluvial plane (Central Italy)

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Keywords: connate water upwelling, natural contamination, alluvial aquifer.

The so-called "natural mineral waters" or "thermal waters" are generally highly saline groundwater, related to peculiar aquifer geochemistry and underground hydrodynamic. These water resources are worldwide known for their therapeutic properties, that pertain to several human health aspects. However, due to the peculiar hydrogeochemistry (i.e. high major ions and trace elements concentrations), these natural mineral groundwaters could concern to their management, especially when they mix with fresh water in shallow aquifers. Considering the current environmental laws, interactions between fresh and mineral waters can represent natural contamination events. Underground hydrodynamics influence the extent of mixing; therefore, understanding aquifer recharge and groundwater flow is essential for effective water resource management. Considering this need, the main aim of this research is to define the conceptual model of the actual hydrodynamic role in connate mineral groundwater upwelling and mixing with fresh water in shallow alluvial aquifers, through a multidisciplinary approach. The data utilized for this purpose comprises geological and geophysical surveys (including boreholes, seismic refraction methods, and electrical resistivity tomography), measurements of hydraulic head, analyses of groundwater chemistry, and physico-chemical water logging.

The selected study area is the Vomano valley, in Central Italy. This area is characterized by a shallow gravelly and gravelly-sandy alluvial aquifer, that shows a thickness of about 5-10 m and whose aquiclude is represented by the marine marly-clayey bedrock (i.e. the post-evaporitic member of the Laga formation). Its recharge is due to the direct rainfall infiltration and the Vomano river leaking in the aquifer. Here, connate natural mineral groundwater rises through the aquiclude highly fractured zone and mixes with shallow groundwater. These connate waters are characterized by very high electrical conductivity, a water-type that is mainly Na-Cl-SO_4, high boron, iron and manganese concentrations. Recently, their suitability for exploitation was assessed, and they were considered eligible to be used for therapeutic purposes (i.e. dermatological and inhalation treatment). However, these mineral waters have never been exploited, and they are still mixing in the environment, posing several concerns to the freshwater use for irrigation purposes.

The first results show that these connate mineral waters represent old seawater trapped during the last sea-level regression and accumulated in fine marine deposits. They are confined and rise through the fractured bedrock due to a pressure gradient. Their zone of influence seems to be very limited in space, suggesting a strong dilution due to the fresh groundwater flow. Nevertheless, increases in the alluvial aquifer hydraulic head during the wet season recharge favour, due to the vertical drainage, the connate mineral water upwelling, instead of provoking dilution.

The mineral-thermal water resources of Verbano-Cusio-Ossola (Piedmont, Italy). Realization of a regional Atlas of both historical and heritage mineral and thermal waters

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Keywords: Verbano-Cusio-Ossola, mineral waters.

In Italy people prefer to consume bottled water rather than tap water. Italians are the biggest mineral water drinkers in Europe, with over 200 liters per year for each person. Every year, 16.5 billion liters of water are bottled in the "Bel Paese", of which almost 15 billion are destined for the domestic market. According to Legambiente datas (https://www.legambiente.it/rapporti-e-osservatori/acque-in-bottiglia/), the mineral water industry in Italy has a turnover of 10 billion euros, with over 260 brands distributed in approximately 140 plants, making Italy the first country in Europe and the second in the world (behind only Mexico) for bottled water consumption.

Based on these data, a mountain province like Verbano Cusio Ossola, situated in the north of Italy, rich in mineral and thermal springs, could forcefully enter the national and global market. Water is really abundant in this area. In the province of VCO there are 295 alpine lakes, of which almost 100 are between the Antigorio and Formazza Valleys. There are also 32 artificial basins, of which 14 were built on pre-existing natural lakes. It is also one of the areas of Italy where precipitation is more abundant and persistent for a large part of the year, effectively eliminating the temporal intervals of water stress. In addition to these resources, 22 mineral-thermal springs have been recognized in this area, to which are added several springs exploited for drinking purposes.

Many mineral-thermal springs are not currently exploited, despite the fact that in the past there were several bottling companies. The variety of lithologies present in the territory, the abundant precipitations and the large quantities of accumulated snow are determining factors for the variety, quality and quantity of mineral and thermal waters.

Considering the potential of these resources, including non-mineral-thermal uses to address possible climate change-induced water crises resulting from global warming, there is a need for a survey of available resources that provides the information regarding quality, quantity, and possible use of the resource in order to plan for environmentally sustainable use of these waters.

In this paper we will proceed with the rediscovery of much of this heritage of this small Piedmontese province, situated between Switzerland and Lombardy, full of potential.

Can machine learning be useful in hydrogeology? A case study of 40 years of potentiometric level monitoring in the Euganean Geothermal Field (EuGF), Veneto region, NE Italy

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Keywords: Euganean geothermal field, deeplearning, potentiometric levels.

The Euganean Geothermal System (EuGS), along with its fields (EuGFs), is a crucial environmental and economic resource, with water temperatures ranging from 63°C to 87°C. In 2006, approximately 15.7 million cubic meters (Mm^3) of thermal water were extracted from 142 wells. The water is primarily used for balneotherapy, serving around 240 pools and supporting a significant regional tourism industry (Fabbri et al., 2017).

The expansion of tourism in the 20th century led to a significant decline in the potentiometric level of the fissured thermal aquifers. Overexploitation caused the depletion of some thermal springs, necessitating stricter regulations on water extraction. A monitoring network has been in place since the 1970s to track aquifer levels and prevent further depletion. Since the 1990s, monitoring measures and flow rate limitations have allowed for the gradual recovery of water levels (Fabbri et al., 2017). The current extraction rate from the mining claims of Abano Terme, Montegrotto Terme, and Battaglia-Galzignano Terme (approximately 14.7 Mm^3/year) is considered sustainable at present. In this context, balanced management is crucial to preserve the resource for future generations, including potential future use for energy purposes. From this perspective, analyzing the variation in potentiometric levels, especially in the area of highest thermal water withdrawal, is essential. Researchers working with long-time series of potentiometric levels often face challenges with missing data. Therefore, our first objective was to reconstruct this long series; all analyses were conducted in the R environment. This objective was achieved using all available 10 monthly time series from 1980 to 2020, including 3 series related to water withdrawals (Abano Terme, Montegrotto Terme, and Battaglia-Galzignano Terme), and 7 series of potentiometric levels from exploitation wells in the EuGF. The R package used for this analysis was “mice” (Multivariate Imputation by Chained Equations; van Buuren & Groothuis-Oudshoorn, 2011), which creates multiple replacement values for multivariate missing data.

Since the potentiometric regime in the EuGF is entirely artificial and linked to the EuGF withdrawal rate, our second and most important objective was to create a machine learning model that connects the input (withdrawals) to our output (potentiometric levels). This model aims to forecast potentiometric levels in the EuGF based on future withdrawal rates. The implemented “DeepLearning” model is built using the R package “keras” (Allaire & Chollet, 2024) and consists of a first 1D Convolution layer, two LSTM layers, a Dense layer, and a final Dense layer. The results, measured in terms of mean squared error (MSE) and mean absolute error (MAE), suggest good performance, as evidenced by the comparison between the real and simulated data for the test set.

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Exploring spring behaviour in the Aosta Valley (Italy): integrated harmonic and isotopic analyses for hydrogeological assessment

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Keywords: alpine hydrogeology, mountain springs, isotopic analysis.

Mountain springs represent a vital component of the drinking water supply system in northern Italy, playing an essential role in meeting the needs of local communities. In recent decades, however, numerous hydrogeological challenges have emerged across the Italian Alps and Apennines, including diminished spring flow and the transformation of perennial springs into seasonal ones. Gaining insight into the recharge processes of these springs is critical for informed and sustainable water resource management.

Since 2010, the Applied Geology Research Group at the Politecnico di Torino has been conducting detailed monitoring activities in the Aosta Valley Region (northwestern Italy) (Gizzi et al., 2022). This work involves the use of multiparameter sensors in several springs—Promise, Entrebin, Gabiet, and Promiod—each situated in distinct mountain catchments. These sensors collect hourly data on water level, temperature, and electrical conductivity. Meteorological data, including precipitation and air temperature, are also gathered from nearby weather stations. To investigate recharge dynamics, hydrograph signals were analysed using Fast Fourier Transform (FFT), which enabled the decomposition of time-series data to identify correlations between discharge patterns, temperature changes, and precipitation events. Isotopic analyses (based on the V-SMOW2 standards) further contributed to the understanding of groundwater recharge origins, employing $\delta^{18}O$ and $\delta^{2}H$ isotopes to estimate the altitudes at which rain and snow infiltrate.

By combining these investigative approaches, the study has provided a more comprehensive view of spring recharge processes. Furthermore, the findings reveal how climatic fluctuations in mountainous regions influence spring discharge, offering valuable information for the development of sustainable management strategies for alpine water resources.

Gizzi M. et al. (2022) - Aosta valley mountain springs: a preliminary analysis for understanding variations in water resource availability under climate change. Water, 14(7), 1004, https://doi.org/10.3390/w14071004.

Thermo-mineral water at the Bagno Grande archeological site (San Casciano dei Bagni, Central Italy): between geological setting and environmental context

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Keywords: hydrogeochemistry, isotopes, archaeology.

Multidisciplinary research at the Bagno Grande archaeological and hydrothermal site integrates hydrogeological, geomorphological, and palynological data to investigate the geological and paleoenvironmental context, with a focus on water as a fundamental element of the study site. In Etruscan and Roman times (5th century BCE to 5th century CE), an important sanctuary is under excavation at Bagno Grande, bringing to light one of the most significant collections of bronze ex votos in the entire Mediterranean area. Hydrogeological monitoring was carried out at six sites (S1-S6) to determine the origin, composition, and evolution of the thermal waters associated with the structural setting of the Mt. Cetona ridge, a tectonically complex area, where deep fluids ascend along faults and mix with shallow groundwater. The surveys combined physico-chemical measurements, major and trace element analyses, and multi-isotopic characterization. Results indicate mesothermal waters with a Ca-SO_4 hydrogeochemical facies, reflecting prolonged flowpaths in deep carbonate and evaporite systems. S1 and S3 (including the historical Bagno Grande spring) show high mineralization (TDS > 2500 mg/L) and high concentrations of Sr, B, and Li, indicating intense water-rock interaction and deep flowpaths. Tritium values support this interpretation, with thermal waters at S3 showing low ^{3}H values, representative of long residence times, and S2 (cold groundwater) characterized by higher values, consistent with shallow circulation. Stable isotopes of water confirm the meteoric origin with recharge from the Mt. Cetona aquifer, while sulfate and strontium isotopes trace a deep evaporitic contribution. Notably, the thermal system exhibited hydrosensitivity to seismic activity in February 2023, showing a sudden drop in temperature and water level at Bagno Grande before a Mw 3.7 earthquake occurred near Siena. It is reasonable to assume that such transient variations were also observed during the development of the archaeological site, potentially reinforcing its significance as a site of cult. Preliminary geomorphological and palynological studies offer a broader paleoenvironmental framework. The geomorphological setting of the area is controlled by Quaternary uplift and widespread outcrops of clay-rich formations, which are prone to river and runoff erosion as well as to landslides. Fault-controlled topography governs spring distribution, and a palustrine sequence provided insights into Quaternary environmental evolution. Geochronological constraints and preliminary pollen analyses from the palustrine sequence sampled in a trench and an Augustan-age well reveal a transition from Upper Pleistocene open forest to an anthropized landscape. Overall, the Bagno Grande site represents a dynamic environment where deep geological processes and human history are closely connected. These insights contribute to sustainable strategies for the conservation of both heritage and thermal resources.

Reconstruction of the Daruvar thermal spring area using geophysical and hydrogeological investigations

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Keywords: carbonate geothermal aquifer, hydrogeological parametrization, geophysical investigation.

Geothermal energy is foreseen as a crucial component for the European green transition. Sustainable utilization of geothermal resources relies on detailed geological, structural, and hydrogeological characterizations of the reservoir. The presented research was conducted in the Daruvar thermal spring area (NE Croatia) for the local-scale geological and hydrogeological reconstruction of the subsurface. This area consists of four thermal springs (temperature up to 48°C) and five boreholes feeding health and recreational tourism facilities, which are a main economic resource in the area.

Conducted investigations included surface geophysical techniques to reconstruct the subsurface geometry and hydrogeological investigations to quantify the hydrogeological parameters of the aquifer. Electrical resistivity tomography (ERT) was employed for the geological reconstruction. In 2021-2022 eight profiles were acquired using an electrical imaging system. Field apparent resistivity data were inverted into 2D resistivity subsurface models, reconstructing the geometries of lithologies and structures in the subsurface (Loke et al., 2013). Hydrogeological investigations consisted of well logging and pumping test of a 190 m deep well. Well logging was conducted after the drilling in 2008, while the pumping test was performed in 2022. The results were analyzed using classical approaches (e.g., Kruseman et al., 2000), determining the porosity (Φ) and permeability (k) of the aquifer.

ERT profiles depicted low resistivity values (10-150 Ωm). Using the stratigraphic logs of the boreholes, three resistivity/geological units were identified: 1) the Quaternary alluvial cover with resistivity of 30-50 Ωm, 2) the Neogene sediments with lower resistivity values (10-30 Ωm), and 3) Triassic dolomites divided into a compact layer (70–150 Ωm) and a fractured layer (20–30 Ωm). Sharp lateral resistivity variations with low resistivity values (5-20 Ωm) were identified. They were interpreted as fracture zones along faults representing preferential pathways for the circulation of thermal fluids.

Results of hydrogeological investigations showed: 1) Φ, obtained from the neutron log of the well, from 0.03 to 9.1% (average = 2.7%), and 2) k, calculated using transmissivity values from the analysis of pumping tests and literature data, from 7.4 to 122.8 D (average = 46 D). The reliability of the hydrogeological parameterization was corroborated by hydrogeological numerical modeling conducted using a DFN approach and based on field structural investigations in an outcrop analog of the aquifer (Kosović et al., 2024).

The obtained results highlight the importance of integrating surface geophysical and hydrogeological approaches to investigate fractured aquifers. These approaches can provide a detailed reconstruction of the reservoir, promoting a sustainable utilization of geothermal resources.

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Hydrological and Geomorphological Features of the Karst Area of the Grassano-Telese Springs (southern Apennine, Italy)

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Keywords: ascending flow, sulfurous springs, collapse dolines.

Geomorphological and hydrological processes are closely interrelated in karst terrains. Two types of karst systems can be distinguished: (i) the epigenic one forms by water infiltrating from the overlying recharge zone and thus develop in genetic relation to the surface landscape; (ii) the hypogenic one forms by corrosion and erosion operated by groundwater of deep origin, ascending from lower formations. Hypogenic karstification characterizes many carbonate karst systems of the Apennine chain (Italy) and is typically associated with aggressive groundwater enriched in endogenic H_2S and CO_2 (Galdenzi & Minichetti, 2017). Here, we focus on the Telese-Grassano karst area (Campania Region), where the relationships between groundwater and karstification processes are evident and result in specific surface landforms. In particular, the area can be considered the most depressed discharge zone of a wider karst system, whose main recharge zone would be located in the Matese Mountains. Large fresh karst springs (Grassano springs) and higher-temperature (thermal) springs enriched in H_2S and CO_2 (Telese springs) are located along the southern side of a carbonate hill (the Montepugliano Mt.), bounding the Telese Plain to the north. Dolines occur in the whole area, generated by the collapse of underground voids affecting both the carbonate bedrock and the sedimentary cover of the plain. A cluster of dolines characterized the Montepugliano Mt., where the groundwater flow concentrates, giving rise to the abovementioned springs. The area shows peculiar hydrological, morphological, and geochemical features, including artesian conditions in the Telese Plain, high density of collapse dolines, acid spring water, constancy of the groundwater temperature and electrical conductivity over time, seasonal fluctuation of the radon activity during the hydrological year. Based on field observations and numerical simulations, these features can be explained by an ascending groundwater flow mechanism in the spring area (Fiorillo et al., 2019). The latter typified discharge zones of wide groundwater systems and has also been detected in other karst areas of the southern Apennine (Fiorillo et al., 2018). Unlike typical karst environments, the caves and dolines of Montepugliano Mt. have no relation to recharge through the overlying surface (Leone et al., 2022), and their formation is due to dissolution operated by groundwater.

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The geothermal resources of Vulcano Island (Aeolian Archipelago, Italy)

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Keywords: geothermal, resources, Vulcano.

In the framework of the PRIN 2022-PNRR program, the geothermal resources of Vulcano Island were evaluated considering available geological, geochemical, and geophysical data as well as the conceptual model of La Fossa magmatic-geothermal system by Cioni and D'Amore (1984). The work was focused on the interpretation of a geochemical dataset comprising (i) 152 groundwater samples from the Vulcano Porto plain and surrounding areas and 12 steam-heated marine waters from the Baia di Levante, all obtained from previous studies and (ii) 4 groundwater samples from the Vulcano Porto plain and 3 steam-heated marine waters from the Baia di Levante collected during this work. The Vulcano Porto plain groundwaters and the steam-heated marine waters from the Baia di Levante are ascribable to eight different chemical types, among which the acidic waters of Na-Cl, Na-Cl(SO_4), and Na-SO_4(Cl) composition could be either volcanic waters generated by condensation of the mixed magmatic-geothermal crater fluids or marine waters heated by absorption of geothermal steam and gases. This genetic dilemma was solved using the stable O and H isotopes of the water-gas system indicating that the waters of interest are generated by mixing of meteoric waters, marine waters, and vapors and liquids produced by boiling of the geothermal endmember, whereas they are not impacted by the magmatic endmember. Having ascertained that the waters under examination are heated by geothermal fluids, the distribution of the P_{CO2} and temperature in the groundwaters of the Vulcano Porto plain was adopted to delimit the areal extension of the underlying geothermal aquifer, which resulted to be 0.777 km^2 based on the P_{CO2} map and 0.752 km^2 based on the temperature map. These figures are in excellent agreement with each other and with the areal extension of the geothermal aquifer obtained from the MT data, 0.7 km^2. These areas from the P_{CO2} and temperature maps were used to calculate the total volume (rock + water) of the geothermal aquifer. This turned out to be of 2.11 - 2.18 km^3, for a useful thickness of the geothermal aquifer of 2.8 km. Adopting the specific productivity of liquid-dominated geothermal systems, 40 $t * h^{-1} * km^{-3}$, the hourly production rate of geothermal fluids resulted to be in the range 84.2 - 87.0 $t * h^{-1}$. Assuming that the temperature of the geothermal aquifer is in the interval 200 - 275°C, an extractable thermal power of 25 ± 6 (1s) MWt was computed.

Acknowledgments: This work was funded by the PRIN 2022 PNRR project, "Thermal model of Aeolian Islands for new perspectives of sustainable exploitation of geothermal resources ", CUP H53D23011420001. This work reflects only the authors' views and opinions, neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

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Structural modeling of tectonically controlled hydrothermal systems in Central Croatia

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Keywords: structural evolution, 2D/3D structural modeling, central Croatia.

Central Croatia possesses numerous geothermal resources that represent potential renewable sources of both raw materials and energy. With a favorable thermal setting due to the tectonic evolution of the Pannonian basin (Horváth et al., 2015), this area is missing detailed knowledge of the geological and hydrogeological subsurface relations promoting the development of intermediate scale hydrothermal systems.

We present the results of surface structural investigations and subsurface reconstructions of the Daruvar, Topusko, and Hrvatsko Zagorje hydrothermal systems as proxies for hydrogeological modeling. Surface investigations incorporated structural measurements of bedding and fractures and structural and geological mapping, while subsurface 2D/3D reconstructions combined the structural and geological data with seismic reflection data and stratigraphic logs of deep wells from hydrocarbon research.

Results on structural data evidenced a correlation between general N-S and E-W striking fold system patterns and cogenetic fracture systems. Mapped fault systems and their kinematic and stress properties suggested preferable stress orientations. They were compatible with the regional stress fields during: 1) the Late Cretaceous-Paleogene Adria-Europe collision (N-S contraction) and formation of Sava Suture Zone (Schmid et al., 2020), 2) the Neogene E-W oriented opening of Pannonian basin, and 3) the Pliocene-Quaternary tectonic inversion due to rejuvenated Adria-Europe N-S oriented compression/transpression. This polyphase tectonic evolution is evidenced within the studied areas, primary Daruvar, Topusko, and Krapina anticlines, where cogenetic footwall reverse faults and fractures show compressional, extensional, and transtensional/ transpressional properties. It promotes the fracturing of the bedrock enhancing the local permeability field in the outflow areas of the hydrothermal systems as corroborated by the high transmissivity values of the reservoirs ($2*10^{-3}$ -$5*10^{-2}$ m^2/s). Quaternary tectonic stresses maintain the aperture of the fractures that favor a quick rise of thermal waters flowing out in thermal springs with temperatures from 25 to 65°C.

Subsurface reconstructions incorporated the construction of eleven 2D composite geological profiles perpendicular to the regional structures, reaching depths of 3-6 km with lengths of 25 km. Profile constructions and 3D modeling were performed within PE Move software (https://www.petex.com/pe-geology/move-suite/move/). 3D models enabled detailed visualization of the subsurface, favoring iterative corrections of the subsurface relations and preliminary computations of rock volumes. 2D/3D geological modeling also highlighted the importance of understanding regional and local structural relations unraveling causative factors for the regional to local flow of the thermal waters.

Acknowledgments: This research was funded by the HyTheC project of the Croatian Science Foundation, grant number UIP-2019-04-1218.

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Drone thermographic survey on fresh/thermal waters in the Euganean Hills area (Italy)

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Keywords: water salinity, irrigation, conductivity.

In the Euganean Hills area, thermographic acquisitions by drone were carried out for the first time in the South-East area, where several thermal springs have been active for centuries. These data were integrated with temperature and electrical conductivity measurements on surface waters.

Methodology - For the thermographic survey by drone, two types of acquisition were conducted: flying at an altitude of 50 m and at 90 m. A multi-parameter probe was used to measure the temperature and electrical conductivity of the waters, which also acquired the pH and redox potential values.

Thermographic survey by drone - The historically known thermal springs were easily identified and hot water emission points linked to horticultural systems, slight leaks from sealed wells, new sources and unspecified injection points were also identified. The injection of hot water into the surface network, used for irrigation purposes, is evident.

In situ measurements of electrical conductivity - The acquired data show that the introduction of hot and saline waters into the surface network could have negative effects on agricultural activities in the area. In fact, the electrical conductivity values obtained fall within risk classes for salinization up to the level of Severe Hazard.

Conclusions - The high sensitivity and spatial resolution of the thermographic survey allows to identify even small bodies of water at relatively low temperatures (~ 20°C).

In the studied area, cold water (fresh) and warm groundwater (saline) mix in the surface drainage; the balance between the two types of water determines the quality of the water for irrigation use and their mixing can be difficult to control.

For the Euganean area, two processes are critical: the decrease in precipitation due to climate change and the increase in the piezometric level of thermal groundwater. Each of the two processes can produce an increase in the salinity of the irrigation water, which is considered with concern by local agricultural companies. In fact, field measurements show that in several sites surface waters have conductivity values that fall into the “Moderate” and “Severe” hazard classes and it should be considered that the spontaneous variability of the system can lead to large and worrying variations in salinity. With drip irrigation the volumes of water supplied are lower, therefore the quality of the water supplied must be absolutely guaranteed. However, although the increase in salinity represents an alarm for several types of crops, it could be transformed into an opportunity to develop other types of crops, which are known to be more tolerant to salt water.

The thermographic survey, accompanied by in situ measurements of temperature and conductivity of surface waters, confirmed the close connection between environmental aspects (such as the spontaneous release of thermal water), the exploitation of natural resources (geothermal energy), economic activities (agri-food) and the impact of climate change.

Origin and water-rock interaction processes controlling the chemistry of thermal and mineral waters in northeastern Italy

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Keywords: north Italy, waters, geothermal.

The Alps constitute the main source of water in northern Italy, supporting diverse terrestrial and aquatic ecosystems and the human water supply. Based on their physicochemical properties, most of these waters are exploited in the beverage industry, balneology, spa therapy and have direct application for low-medium enthalpy geothermal applications. Despite the undoubted importance of the Alpine waters, their circulation patterns and water-rock interaction processes remain poorly constrained. This study is aimed at filling this knowledge gap by means of an extensive survey of geochemical and isotope parameters on thermal and mineral waters springing in the easternmost Eastern and Southern Alps sectors and the northeastern area of the Po Plain (covering Trentino Alto-Adige, Friuli Venezia Giulia and part of Lombardia and Veneto Regions). The objectives were to: (i) investigate the main factors controlling the chemistry of the eastern Alps waters, inferring circulation circuits and sourcing areas; (ii) provide the very first evidence on the geothermal potential related to the different hydrothermal systems of the study area.

A total of 68 waters from springs and wells were surveyed. The total dissolved solid values were highly variable (from around 100 to 20,000 mg/L) whilst water temperatures varied from < 10°C to 82°C, with the highest temperatures measured in the waters discharging from the areas of southern Garda Lake, the Grado-Tagliamento, Bormio Terme and Colli Euganei. The hydrochemical characteristics included the Ca/Mg-HCO_3, Ca/Mg-SO_4, Na-Cl and Na-HCO_3 facies, indicating variable interaction with carbonate rocks, sulphate- and chloride-rich evaporite layers and silicate formations. The δD- and $\delta^{18}O$-H_2O values inferred a predominant meteoric origin of all waters except for those from the Grado-Tagliamento area, characterised by mixing with seawater. Dissolved gases spanned from N_2- to CO_2-dominated, with a few samples exhibiting a biogenic CH_4-enrichment. The $\delta^{13}C$ values supported a biogenic origin of CO_2 for almost all samples, except a few samples showing relatively heavy $\delta^{13}C$ values that pointed to C-inputs from thermo-metamorphic reactions of limestones. The relatively high $^3He/^4He$ ratios corrected for air contamination (R/Ra of ~ 3) characterising the dissolved gases from Recoaro Terme and Valli del Pasubio implied a significant contribution of mantle He, possibly favoured by the occurrence of deep faults. Equilibrium temperatures estimated with the SiO_2 geothermometers reveal temperatures of interest for geothermal exploration (around 70-120°C) in four different areas: i.e., the well-known hydrothermal systems of southern Garda Lake, Bormio Terme and Colli Euganei, but also the Grado-Tagliamento area. These findings highlight an intricate circulation system for eastern Alps waters at variable depth and involving different rock formations, reflecting the highly complex local geological and structural setting in the area.

Integration of geo-environmental indices as an operational tool for the evaluation of groundwater quality in the eastern sector of the Po plain (northern Italy)

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Keywords: geo-environmental indices, groundwater quality, Po plain.

In recent decades, climate change and increasing anthropogenic pressure have resulted in, on one hand, a rise in water demand for agricultural, domestic, and industrial uses, stressing aquifer systems and on the other, the occurrence of widespread groundwater contamination phenomena. The intelligent exploration and sustainable management of groundwater resources are fully aligned with the development goals (SDG) of the United Nations.

In this context, the present study—carried out within the framework of the BePepAred project—conducts an assessment of groundwater quality for drinking water and irrigation purposes in the eastern sector of the Po Plain (Ferrara Province, Northern Italy), using geo-environmental indices and analyzing their evolution over time.

To this end, analytical data from over 300 groundwater samples collected from the first and second confined aquifers, over a 12-year period, were processed. Specifically, 16 geo-environmental indices were calculated to evaluate: a) drinking water suitability (NPI, RI, PIG, WQI, WPI); b) irrigation suitability (SAR, KR, %Na, PS, MAR, RSC, SSP, TH, PI, IWQI, TDS), including their temporal evolution.

The integrated analysis of the data highlighted that: a) combining multiple indices increases the reliability, accuracy, and robustness of groundwater quality assessments; b) it is effective to identify a subset of indices that reflect the impact of specific elemental concentrations; c) it allows for the identification of areas where the aquifer shows greater critical conditions.

The results obtained may contribute to the processes of management and protection of groundwater resources.

Implications of pumping tests results in hydrothermal areas for the sustainability of groundwater abstraction

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Keywords: thermal waters, pumping tests, sustainable yield.

Thermal waters used for health, wellness and recreational tourism are frequently extracted via wells. These withdrawals can impact both the quantity and quality of the resource supplying health resorts, spas and thermal water parks. This is economically relevant, as European and Italian legislations mandate the long-term constancy of thermal waters composition and temperature. This study investigates the impact of groundwater pumping on the quantity and quality of water used in the thermal centers. To this end, the aquifer response to pumping has been examined in two case study areas. The first case study focused on the hydrothermal area of Viterbo (central Italy), where calcium-sulfate waters with temperature ranging from 40 to 62°C are tapped for spas from springs and wells. In this area, the results of two pumping tests carried out in wells intercepting thermal waters in fractured flysch were analyzed. The second case study concerns the Island of Ischia (southern Italy), where thermal waters with different compositions (from calcium-bicarbonate to alkali-chloride) and temperature (from 13 to 90°C) supply numerous spas, primarily through wells located along the coastal strip. In this case, the results of four selected pumping tests conducted in wells penetrating volcanic and pyroclastic rocks were considered. In both cases, the trends of drawdown, temperature and electrical conductivity of water in the pumping well and in piezometers were interpreted considering the local stratigraphy and boundaries of the intercepted aquifers. In the Viterbo hydrothermal area, the pumping tests highlight the interactions between deep and shallow aquifers having different water qualities. The exploitation from these two aquifers is governed by the hydraulic conductivity and thickness of the intervening aquitard which maintains the hydrogeological equilibrium between the two overlapping aquifers. In the Ischia case study, the quality of groundwater extracted from wells appears to be influenced by the distance of the wells from the coastline, the lithology of the intersected aquifer formation and the groundwater temperature range of the hydrothermal system. Both case studies suggest that the exploitation of thermal waters via wells must be adapted to the local aquifer response to pumping in order to ensure the long-term maintenance of water quantity and quality of water for spa industry use.

Hydrogeochemical zonation across the Apennines: from Umbria Thermal Waters to Marche Saline Springs (Central Italy)

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Keywords: emotion project, thermal waters.

The Central Apennines is a fold-and-thrust belt, verging towards E-NE and displaced by normal (NNW-SSE) and strike-slip faults with N-S and E-W orientation. It comprises the boundary between the Tyrrhenian Umbria-Tuscany extensional area and the Adriatic compressional zone. The different tectonic settings of the two sides of the Apennines promote different geochemical features of the circulating fluids. The western Umbria side is affected by thermal anomalies, geothermal areas, and active CO_2 degassing. In contrast, on the Eastern Marche side, the presence of foredeep basins enhances the presence of hydrocarbon reservoirs, mud volcanoes, and highly salty mineral waters. With a few exceptions, the two sectors have frequently been studied separately from a fluid geochemistry perspective.

In the framework of the EMOTION Project, devoted to the geochemical characterisation of geothermal manifestations in central-northern Italy and the development of a national geothermal fluid web portal, we performed a detailed geochemical and isotopic characterisation of the main thermal and mineral-saline groundwater in Umbria and Marche Regions.

An extensive database of groundwater composition, including about 1000 groundwater analyses, was compiled from the available scientific literature and other data sources. Following a detailed examination of the database, which also includes outdated and not always complete datasets, and taking into account thermal anomalies and other relevant geochemical-isotopic indicators, a selected number of springs and wells were identified for a detailed geochemical survey. Seventeen and twenty-two water samples were collected in Umbria and Marche, respectively, for the analysis of physicochemical parameters, major cations and anions, trace elements, dissolved gases, and helium, water, sulfur, and carbon isotopes.

Preliminary results indicate that the thermo-mineral waters of the Umbria region are generally brackish (mean TDS 2.3 g/L), with temperatures ranging from 15 to 30°C (mean 20°C) and chemical compositions spanning from Ca-HCO_3 to Ca-SO_4 and Na-Cl, with some Na-HCO_3 facies. On the contrary, the waters of the Marche region show chemical composition between Na-Cl and Ca-SO_4, with high-to-very high salinity levels (mean of 24 g/L and values up to 183 g/L) and lower temperatures, always below 20°C, with the notable exception of Acquasanta Terme (up to 30°C).

The results of this ongoing study will provide a better understanding of the relationship between the contrasting tectonic settings that characterise the two sides of the Apennines chain and help depict the regional circulation path of the fluids and the regional convective heat flow of Central Italy.

Numerical modelling for sustainable mine water management

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Keywords: mine water management, numerical modelling, environmental sustainability.

There is currently no standardised approach to the modelling of groundwater flow in the mining industry. Generally, three approaches are used: the equivalent porous media (EPM) procedure, which takes into consideration the rock mass and its discontinuities as continuous, the discrete fracture network (DFN) method, based on the hydraulic properties of discontinuities, natural and/or anthropic, of the rock mass, and the hybrid approach, a combination of the above. To evaluate the best approach, a mine located in the Tuscany region, Italy, was selected as a case study. The mine was chosen for the availability of data covering a time span of almost 100 years, from around 1920 to date. The mine is part of a complex of five, joined at -200 m above sea level (asl). It was active until 1981 and was mined for pyrite extraction. When the excavation activities ceased, natural and managed flooding events occurred, bringing groundwater heads at the current -95 m asl. The groundwater heads are maintained via two pumping wells, active 24/7. Using FEFLOW 7.01, a 3D numerical model of the mine was developed using the hybrid approach. The rock mass was represented as EPM while faults and mining infrastructures, such as tunnels, shafts, and wells, were simulated as discrete elements. The model was calibrated in transient regime, reproducing the progressive mine flooding that occurred between 1995 and 2010. Based on the data obtained from the calibrated model, a forecast simulation will be performed to reproduce the effects of the rising water level after shutting down the pumping well systems, in order to assess if the natural drainage tunnel located at +70 m asl will allow water to flow out by gravity.

S23.

Geomaterials for a sustainable economy: advancements in the state-of-the-art, innovative characterization, and cutting-edge applications

CONVENERS AND CHAIRPERSONS

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Revitalizing quarry landscapes: geotourism and waste reuse in the Buddusò–Alà dei Sardi District

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Keywords: Sardinia, granite extractive waste, rehabilitation.

Ornamental granites have been quarried in Sardinia since prehistoric times, gaining international recognition during the 20th century. However, the granite industry has experienced a sharp decline since the early 2000 leaving behind millions of cubic meters of granite waste accumulated along their perimeter. These waste deposits not only contribute to landscape degradation but also pose geotechnical hazards and potential risks of soil and groundwater contamination.

Furthermore, the decline of this industry has reduced employment opportunities, accelerated youth outmigration and exacerbating demographic aging in Sardinia's inland regions. In response, this study proposes a framework to valorize former quarry sites and their associated scraps by integrating environmental rehabilitation with geotourism and cultural heritage preservation.

The recovery of critical and conventional raw materials from granite extractive waste needs a broader post-extractive strategy. Quarry restoration in these contexts should extend beyond simple ecological restoration to incorporate functions related to tourism, culture, and environmental education. This approach entails both the preservation of the industrial and morphological identity of quarry landscapes and the development of multifunctional spaces that support sustainable local development.

In Sardinia, the extractive industry is deeply intertwined with the archaeological and cultural heritage. Over 6800 archaeological sites, ranging from proto-nuraghes and domus de janas to menhirs and giants' tombs—are documented throughout the region. In several areas, particularly in the Buddusò–Alà dei Sardi district, granite quarries and archaeological structures coexist spatially. This overlap, together with the strong cultural connection that local communities maintain with granite—evident in its extensive use in architecture and through events like the "Spirit of Rocks" festival—suggests the potential for identity-based, participatory planning processes.

Drawing from international and local best practices, such as the rehabilitation of the Naxos marble quarry (Kaliampakos & Mavrikos, 2006) and the 'visitor trail' developed in the Orosei marble basin (Careddu et al., 2013), the creation of a 'Granite Trail' in the Buddusò–Alà dei Sardi district is proposed. This trail would connect disused quarrying sites with nearby archaeological landmarks, repurposing these spaces as open-air museums, educational hubs or cultural centers.

Achieving this vision will require a coordinated, interdisciplinary planning effort involving geologists, archaeologists, urban planners, engineers, sociologists, public institutions, quarry operators, and local communities. This model of landscape transformation could serve as a replicable blueprint for other post-industrial regions seeking to reconcile environmental restoration with cultural and economic renewal.

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Sustainable stabilization of bioclastic calcarenites through microbial carbonatogenesis: a lab-scale study for Cultural Heritage applications

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Keywords: bioconsolidation, carbonates, laboratory experiments.

Bioconsolidation represents an innovative and sustainable approach in geomaterial conservation, leveraging the carbonatogenic activity of bacteria to enhance the structural stability of weathered stones through calcium carbonate precipitation. While widely applied in soil consolidation and cement repair, its adoption in Cultural Heritage remains limited due to invasive sampling constraints. In this study, we investigate the potential of *Lysinibacillus fusiformis* 3.20 for the bioconsolidation of Macco, a highly porous bioclastic calcarenite characteristic of the hypogeal Etruscan tombs in the UNESCO World Heritage Site of Tarquinia (Italy). This microbial-based technique aligns with circular economy principles by offering a low-environmental-impact alternative to traditional consolidants. A laboratory-scale experimental campaign was carried out to assess the impact of two application methods—immersion and spraying—on the mechanical and petrophysical properties of Macco. We evaluated variations in weight, porosity, seismic wave velocity and uniaxial unconfined compressive strength (UCS). Both treatments promoted carbonate precipitation and led to a general reduction in porosity and increase in seismic velocity. However, the immersion method showed a more consistent correlation between porosity reduction and increased UCS, likely due to better control over environmental variables. The spraying method, although promising, was more susceptible to external factors such as evaporation and uneven distribution of the bacterial solution.

Our findings confirm the suitability of bioconsolidation for the stabilization of calcarenite substrates and provide a scientific basis for developing targeted, non-invasive conservation strategies in archaeologically and cultural contexts.

Origin and mineralogical-geochemical characteristics of fluorite deposits in the Pollino Area (Mormanno, Southern Italy)

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Keywords: fluorite, Pollino Area, crystals.

Fluorite (CaF_2) is a mineral of significant scientific and industrial importance, commonly associated with specific geological settings. The Mormanno area, located in northern Calabria within the Pollino National Park, hosts fluorite outcrops whose origin and genesis remain poorly investigated to date, despite global interest in similar contexts (Wilkinson, 2001). Studies on similar mineralizations in the Southern Apennines (Richardson & Holland, 1979; Dattola & Barone, 2024) suggest an origin related to the circulation of mineralizing fluids. In this context, the deposition of fluorite, known to be influenced by hydrothermal conditions, may result from the interaction between circulating fluids and local metamorphic processes. This study aims to define the origin of fluorite in the Pollino Area (Mormanno, Southern Italy) by analyzing its mineralogical relationships in detail and assessing the impact of growth processes on its formation. For this purpose, representative samples were collected from the outcrop area and subjected to a series of mineralogical and chemical analyses, including XRPD, SEM/EDS, TEM/EDS, IR, DSC-TG, and ICP-MS. Preliminary data indicate that fluorite occurs in crystals with variable morphologies, ranging from subhedral forms with partially developed faces to anhedral, irregular grains. Crystal sizes vary from a few millimeters up to 10 cm. The dominant coloration is violet, with shades ranging from light lilac to deep purple. Some crystals exhibit color zoning, and in certain cases, remnants of host rock are attached, suggesting possible variations in chemical composition or growth conditions during their formation. This research provides new insights into the geological evolution of the Pollino area and characterizes fluorite as both a scientific marker and a mineral of notable aesthetic value.

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Naturally occurring asbestos (NOA)–related water contamination in the Basilicata Region, Southern Italy

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Keywords: waterborne asbestos, naturally occurring asbestos, hydrogeological pathways.

Asbestos refers to a group of six fibrous silicate minerals historically employed for their excellent mechanical and thermal properties. Due to their proven carcinogenicity, their use is now banned or restricted in many countries. Inhalation of asbestos fibers is associated with serious diseases such as asbestosis, lung cancer, and mesothelioma. Naturally occurring asbestos (NOA) is frequently found in ophiolitic rocks, where weathering and erosion may release fibers into the environment, including water systems (Bloise et al., 2017). To date, asbestos monitoring has focused primarily on airborne fibers, while its occurrence in water has been only marginally investigated. Waterborne asbestos raises concerns regarding its potential transfer from water to air in domestic, public, and occupational settings (Webber et al., 1988). While the adverse health effects of asbestos inhalation are well established, a clear agreement has yet to be reached on a safe threshold for asbestos contamination in water (WHO, 2021). This study aims to evaluate the extent of asbestos contamination in groundwater and public water supplies within the Pollino Massif area (Basilicata region, Italy). To this end, an extensive analytical investigation was carried out on mineral fibres identified in 55 water samples, using SEM-EDS, TEM-EDS, and μ-Raman spectroscopy. These results, integrated with mineralogical, hydrogeochemical, and geological data, seek to characterize the types and concentrations of fibres, identify their source lithologies, and reconstruct their potential transport pathways within the environment. The concentration of water-dispersed asbestos fibres (C, in f/L) revealed tremolite as the most abundant fibrous phase. Chemical characterization and morphological dimensional analysis of all fibres observed indicated that tremolite, actinolite, chrysotile and anthophyllite exhibited variability in fibre dimensions, with a significant proportion falling within the WHO criteria for respirable fibres. These findings highlight the necessity of considering groundwater as a potential pathway for asbestos contamination and reinforce the importance of conducting comprehensive assessments and further research to mitigate health risks associated with asbestos exposure through water sources.

Aknowledgment: This work was funded by INAIL - BRIC 2022 project (grant number ID 67; CUP: B87G23000090005).

Bloise A. et al. (2017) - Naturally occurring asbestos: potential for human exposure, san Severino Lucano (Basilicata, southern Italy). Environ. Earth Sci., 76(19), 1-13, 10.1007/s12665-017-6995-9.

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World Health Organization (2021) - Asbestos in Drinking Water: Health Risks and Regulatory Considerations, 32 pp.

Metakaolin- and Zeolite-based Geopolymers: mineralogical and mechanical characterizations

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Keywords: geopolymers, metakaolin, zeolite.

In the context of the ecological transition and the promotion of innovative materials for a sustainable economy, geopolymers represent a promising alternative to traditional cement-based binders due to their sustainability, versatility, and high mechanical performance. The present study proposes an experimental approach to characterize five distinct geopolymer mixtures. These were obtained by essentially varying the starting material and the silica/alumina ratio. Four of these were made from metakaolin (Boscia et al., 2024), a material that has been extensively utilized in alternative binder research, while one of the mixtures was formulated by adding 10% by weight of natural zeolites, derived from the waste processing of Campanian tuffs. Among the metakaolin-based mixtures, one was modified by adding a superplasticizer that is commonly used in traditional cements, which was produced by BIQEM SpA.

To comprehend the mineralogical and structural characteristics of the materials obtained, a wide range of analytical techniques was employed; such as: Fourier Transform Infrared Spectroscopy in Attenuated Total Reflectance (ATR-FTIR) and Quantitative X-Ray Powder Diffraction (Q-XRPD), X-Ray Fluorescence (XRF), Thermogravimetric Analysis (TGA) coupled with Differential Scanning Calorimetry (DSC) and Scanning Electron Microscopy (SEM) coupled with an Energy Dispersive microanalytical system (EDS). Furthermore, the porous system was investigated using Mercury Porosimetry (MIP) and Hydric tests, while the mechanical performance was evaluated using Compression and Flexural tests.

Spectroscopic and Q-XRPD analysis revealed that, among the metakaolin-based mixtures, those characterized by a higher silica/alumina ratio (4.98 vs. 3.53) showed a higher degree of alkaline activation. This result was further substantiated by SEM observations, which revealed a significantly more compact microstructure for the same samples compared to the mixtures with lower ratios.

The data from the mechanical characterization confirmed this evidence; in fact, the compressive strength value is 42 MPa on the 28th curing day, compared to lower compressive strength values recorded for the other samples (in the order of a some MPa).

The zeolite-containing sample also shows a good activation capacity, although the material has a lower compressive strength (25 MPa after 28 days of curing), albeit comparable to that of conventional mortars. To complete the experimental investigation, a life cycle assessment (LCA) of geopolymer products will be conducted to quantify the resulting environmental impacts.

Boscia S. et al. (2024) - Mineralogical characterization and alkaline activation of commercial metakaolins: potential applications. In: Geology for a sustainable management of our Planet. Abstract Volume, Joint Congress of Società Geologica Italiana (SGI) and Società Italiana di Mineralogia e Petrologia (SIMP), 3-5 settembre 2024, Bari.

Technical performance and pozzolanic potential of volcanic aggregates for lightweight and eco-compatible mortars

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Keywords: pozzolanic lightweight mortar, vesiculated basaltic scoria, physical-mechanical properties.

This study explores the technical and pozzolanic potential of two types of volcanic rocks from Sardinia: basaltic scoria and pumice-cineritic pyroclastic material of rhyolitic composition, used together to produce lightweight mortars with low environmental impact.

The experimentation focused on studying the pozzolanic activity of the two volcanic materials in various mortar mixtures, prepared with different grain sizes of vesicular basaltic scoria aggregates depending on their use as plasters (< 100 μm, < 2 mm) and as screeds (< 6 mm); in the screed mixes, micronized rhyolitic pyroclastic material was also used. Two types of binder were employed: lime putty and ground hydrated lime. The specimens were subjected to a series of physical-mechanical tests to determine various properties (density, porosity, compressive strength, dynamic elastic modulus, vapor permeability, capillary absorption) and mineralogical analyses using X-ray diffraction (XRD). Particular attention was given to the time evolution of physical properties, with measurements at 7, 28, and 60 days of air curing. Mortar specimens cured in a controlled environment (without CO_2) were also studied to verify the possible pozzolanic reactivity between the basaltic scoria, rhyolites, and hydrated lime in the absence of carbonation.

The results show that the mechanical strength of the mortars cured in air is mainly positively influenced by the carbonation of the binder, which occurs earlier than the formation of new hydraulic products, even though the rhyolitic pyroclastic material and the scoria themselves show some pozzolanic reactivity induced by their amorphous glassy component (generally not exceeding 50%). After 28 days of curing, the mortar specimens showed compressive strengths ranging from 0.53 to 0.83 MPa for plaster mortars and from 1.14 to 1.33 MPa for screed mortars; these values increased respectively to 0.61–0.95 MPa and 1.1–1.74 MPa at 60 days. The total porosity of the plaster mortars decreased from 53–58% to 35–39% at 28 days and to 33–36% at 60 days, while for the screed mortars it decreased from 50–53% to 41–46% and finally to 35–44%.

The granulometry of the volcanic scoria aggregates had a subordinate effect on the physical-mechanical performance of the mortars, while their peculiar vesicularity provided good lightweight properties to the products. The good mechanical strength is ensured by the combined use of the pyroclastic material, which showed, between the two, better surface reactivity with lime. The mixtures proved compatible with lime-based systems, favoring the production of lightweight, low-impact mortars with good properties for applications in the restoration of cultural heritage. Overall, the use of local volcanic materials can represent a strategic resource to produce eco-compatible mortars, contributing to the sustainable enhancement of Sardinian georesources and offering new perspectives for green construction and the restoration of historical heritage.

From risk to resource: the environmental and strategic potential of serpentinites in the Pollino Ophiolite (Southern Apennines)

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Keywords: serpentinite georesources, critical raw materials, environmental risk.

Serpentinites pose significant environmental and health concerns due to the presence of asbestiform minerals—chrysotile, antigorite, and amphiboles (e.g., tremolite, actinolite)—capable of releasing hazardous fibers and heavy metals like Cr and Ni. These elements are regulated under European Directive 2003/18/EC and Legislative Decree 152/2006 (Rizzo et al., 2020).

A study was conducted on serpentinites from the Frido Unit in the Southern Apennines, with samples collected at Seluci and San Severino Lucano (Lauria, PZ), within the Pollino Massif, part of the Liguride Complex. These rocks represent remnants of Jurassic oceanic lithosphere emplaced during the Apennine orogeny and are characterized by intense deformation and metasomatic overprinting (Rizzo et al., 2024)

This study aimed to assess the structural, mineralogical, and geochemical characteristics of serpentinites, with a focus on critical metal content and implications for environmental risk and resource valorization. Petrographic analysis showed mesh and lepidoblastic textures with serpentine minerals, talc, chlorite, magnetite, relict olivine and pyroxenes, and abundant carbonate veins. In accordance with Rizzo et al., 2020, these features reflect multiphase serpentinization under HP/LT blueschist and subsequent greenschist metamorphism.

XRF and ICP-MS analyses confirmed high contents of SiO_2, MgO, and Fe_2O_3, and elevated concentrations of Ni and Cr, which frequently exceed Italian soil quality thresholds. These findings suggest that these serpentinites may be considered a potential secondary source of strategic raw materials, as Ni and Cr are listed among the EU's Critical Raw Materials (Hool et al., 2024).

These results highlight the dual significance of Pollino serpentinites: while they represent a potential environmental hazard due to the release of hazardous fibers and toxic metals, they also constitute a promising resource for the recovery of critical raw materials and for CO_2 mineral sequestration through natural carbonation processes. This duality emphasizes the need for integrated strategies that combine environmental risk assessment with sustainable exploitation of ophiolitic georesources in line with EU climate and resource policies, as suggested by Rizzo et al., 2024.

Hool A. et al. (2024) - Challenges and opportunities of the European Critical Raw Materials Act. Miner. Econ., 37, 661-668, https://doi.org/10.1007/s13563-023-00394-y.

Rizzo G. et al. (2020) - An Integrated Study of the Serpentinite-Hosted Hydrothermal System in the Pollino Massif (Southern Apennines, Italy). Minerals, 10(2), 127, https://doi.org/10.3390/min10020127.

Rizzo G. et al. (2024) - Serpentinites of the Pollino ophiolite massif (Calabria, southern Italy), mineralogy, petrography and future perspectives. Period. Mineral., 93(3), 221-232.

From the mine to the extraction plants of critical materials. Step by step ecological and innovative treatments of mining products and residues

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Keywords: sustainable mining activity, refining chemical plants, closed and modern plants.

Current mining technology is highly advanced in any sector where it is applied, whether we are talking about primary or secondary mines. This technology can be exemplified in a production line consisting of plants based exclusively on physical - and therefore ecological - principles of crushing, concentration, magnetic, electromagnetic and/or electrostatic separation and vibrating tables.

These systems, that exclude the use of chemical plants (cyanide, mercury or flotation agents) in the mine, reduce the possibility of pollution risks in the event of a direct accident because the dispersion of chemically treated materials into the environment is not possible under any circumstances. In these situations, in order to minimize the environmental impact, particular attention must be paid only to the release of dust during crushing as well as to the reuse of water used in concentration and separation plants.

As regards instead refining plants, which cannot do without chemicals, modern plants must represent closed systems, that is, plants where nothing harmful must be dispersed into the environment nor can escape even in the event of an accident. It is therefore necessary not only to carefully choose low-toxicity solvents, but also to develop effective systems for the complete recycling of exhausted ones.

Utilization of Sicilian clayey sediments and industrial process waste in sustainable earthen mortars: pathways toward low-impact and recyclable building materials

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Keywords: earthen mortars, eco sustainable production, Sicilian clayey sediments.

It is now well established that, in the field of construction, it is important to combine the need to minimize waste and scraps—thus favoring environmental protection—with the requirement to create building products that are optimal for structural integrity and livability (Bollini, 2002).

The ITER project (Ecological and Recyclable Earth Plasters) focuses on an experimental process for plaster production, with a particular emphasis on the use of raw earth materials mixed with natural reused products.

Raw earth mortars represent a valuable resource in the construction field, used as coatings, as they have properties and hygrometric characteristics that guarantee improved habitability, thanks to their ability to absorb atmospheric pollutants, resulting in a significant improvement in air quality. Raw earth is also inexpensive and readily available; it is a very versatile material for building eco-friendly, zero-impact homes.

This type of mortar, although it has great application potential, lacks clear definition and valorization, resulting in limited use (Scudo & Bonati, 1994; Rauch & Kapeinger, 2001; Achenza & Sanna, 2009).

This communication aims to characterize the petrographic, mineralogical, and chemical properties of three Sicilian clayey sediments, used as binders, together with stone-processing waste such as marble sawing sludge and crushed Mt Etna basaltic rocks (locally named “azolo”), in order to evaluate and define their potential use as mortars, optimize performance, and promote circular processes using natural materials.

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Hydrous Borates under extreme conditions: insights for neutron shielding concrete design

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Keywords: geomaterials, borates.

Hydrous borates (e.g., colemanite, kernite, ulexite, borax, and tincalconite) are the primary mineral commodity of boron—an element of both geochemical significance in pegmatitic and granitic systems and strategic value in various technological applications. The crystal structure of these minerals is built up by the $B\varphi_x$ units (where φ represents O^{2-} or OH^-), forming tetrahedral or planar trigonal groups. These units are connected to form polyionic clusters, in turn connected to alkali and alkaline-earth metal polyhedra (mainly Na^+, K^+, Ca^{2+}, Mg^{2+}). A pervasive hydrogen-bonding network, involving H_2O molecules and OH^- groups, further stabilizes the crystalline edifices (Comboni et al., 2021; Pagliaro et al., 2021).

Recent experiments, performed over the last five years, have explored the behavior of hydrated borates under high-pressure and high-temperature conditions, unveiling phase transitions and deformation mechanisms leading to a number of high-pressure polymorphs. The non-ambient condition behavior, in response to perturbative parameters (i.e., temperature, pressure, and leaching), is now applied to design neutron-shielding materials, due to the exceptional neutron absorption cross section of B (in particular 10B). This contribution presents an overview of the current state of art on hydrated borates, highlighting their potential in the development of neutron-shielding components (in the form of tiles or panels) made by Sorel cements and borates aggregates.

Comboni D. et al. (2021) - Crystal structure of the high-P polymorph of $Ca_2B_6O_6(OH)_{10}\cdot 2(H_2O)$ (meyerhofferite). Acta Crystallogr. B, 6, 940-945, https://doi.org/10.1107/S2052520621009768.

Pagliaro F. et al. (2021) - Thermal and compressional behavior of the natural borate kurnakovite, $MgB_3O_3(OH)_5\cdot 5H_2O$. Constr. Build. Mater., 266, 121094, https://doi.org/10.1016/j.conbuildmat.2020.121094.

Chemical and isotopic (Sr, Nd) analysis of the Nurra basin bentonites (NW Sardinia, Italy)

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Keywords: bentonite, isotopes, smectite.

The Nurra bentonite basin, located in northwestern Sardinia, represents one of the most significant bentonite mining districts in Europe. Among its deposits, the S'Aliderru site stands out for its production, exceeding 300,000 tons/year of material. The bentonite mineralization in this basin is genetically linked to the alteration of calc-alkaline pyroclastic rocks of Oligo-Miocene age. This study investigates the magmatic provenance and alteration processes responsible for bentonite formation by analyzing samples from the two main deposits, S'Aliderru and Sa Pigada Bianca, and from the Mandra Ebbas exploration permit area. A total of 30 samples, including tuffs and associated bentonites, were characterized through geochemical analysis of major and trace elements, as well as Sr-Nd isotopic analysis. The geochemical data reveal a systematic depletion in SiO_2, K_2O, and Na_2O, coupled with an enrichment in Al_2O_3, MgO, and Fe_2O_3, consistent with argillic alteration. Trace element patterns are enriched in Ba (with the highest variability), Li and V, and are depleted in Sr and Rb. Isotopic compositions show $^{87}Sr/^{86}Sr$ values ranging from 0.706752 to 0.710448, and $^{143}Nd/^{144}Nd$ values ranging from 0.512279 to 0.512492. Geochemical and isotopic variations are observed at both deposit and basin scales. The poorly variable Nd isotopic signatures are coherent with the Oligo-Miocene volcanic rocks of the region. Furthermore, the broader variability in Sr isotopic ratios implies the involvement of multiple alteration processes, potentially including interaction with seawater and/or hydrothermal fluids. Interestingly, the highest quality facies have extremely high $^{87}Sr/^{86}Sr$ values. These findings underscore the geochemical complexity of the Nurra basin and point to the need for further multidisciplinary investigations to construct a comprehensive genetic model at the basin scale.

A Deep Learning-basedestimation of glass transition temperature and melt viscosity

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Keywords: glass transition, melt viscosity, deep learning.

The accurate determination of glass transition temperature (Tg) and viscosity (η) is a critical aspect in both volcanology and industrial applications, the first defining the transition of an amorphous solid from a rigid state to a more viscous one while the latter quantifying a material's resistance to flow. In volcanology, viscosity controls magma dynamics, eruption styles, and lava emplacement, directly affecting hazard assessments and interpretations of planetary volcanic activity. In industry, viscosity is essential for optimizing the processing, shaping, and performance of amorphous materials like glasses and ceramics. However, traditional methods for measuring Tg and η are often complex, time-consuming, and require specialized equipment. This study introduces a novel chemically-driven model based on neural networks capable of simultaneously estimating Tg and temperature-dependent η by leveraging easily accessible physical properties and chemical composition. The proposed model demonstrates its ability to learn the correlations within a diverse dataset of glassy systems (from magmatic to industrially relevant silicate compositions), achieving promising predictive performance. By effectively utilizing both physical and chemical descriptors, this work offers a pathway towards more efficient material design and potential prediction also for elastic properties, reducing the reliance on extensive experimental characterization.

Atomic- to nanoscale characterization of calcium silicate hydrates through X-ray total scattering methods

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Keywords: calcium silicate hydrate, debye scattering equation, wide-angle x-ray total scattering.

Calcium silicate hydrate (C-S-H) is a poorly crystalline, nanostructured phase constituting the main binding component in conventional Portland cement based cementitious materials, responsible for their chemical and mechanical properties. Blended cements and alternative binders imply the partial or total replacement of Portland cement in the binder's formulation, decreasing the carbon footprint and boosting the sustainability of the construction sector. Alternative formulations lead to higher complexity in reacting phases assemblage, thus the chemical-mineralogical and microstructural features of hydration products, which also incorporate Al (e.g. C-A-S-H) and alkali metals, depart from that of the C-S-H found in traditional cements.

Achieving the detailed description at the atomic scale of the most relevant binding phases is crucial to fine-tune the paste functional properties, in terms of compressive strength and durability, at the macro-scale. This, however, represents a challenging task because of the chemically complex and structurally disordered nature of these phases. Innovative and advanced methods are required to go beyond the state-of-the-art.

To this aim, synchrotron wide angle X-ray total scattering (WAXTS) experiments coupled with an advanced atomistic modelling approach are applied to pure C-S-H and C-A-S-H samples. Atomistic models for these phases were developed and used to simulate the experimental WAXTS pattern through the Debye scattering equation. Atomistic models were optimized and refined against the experimental WAXTS patterns, integrating complementary information on the structural local order from ^{29}Si and ^{27}Al solid-state nuclear magnetic resonance. C-S-H and C-A-S-H nanoparticles were modelled as an assembly of layers composed of 7-fold coordinated Ca atoms and decorated by (Al- substituted) silicate dimers and chains. The structural layers are a few tens of nanometres in length and width, with a crystal structure resembling that of a defective tobermorite but lacking ordering between stacking layers. Results provided a comprehensive description of the structure, size and morphology of C-S-H and C-A-S-H nanoparticles from the atomic to the nanometre scale. Such information can be effectively transferred to more complex systems, e.g. alkali activated materials, to quantify the precipitation of newly formed hydration products within a multi-phase matrix.

Investigating the composition of asbestos bodies from occupationally exposed individuals via X-ray Absorption Spectroscopy

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Keywords: asbestos bodies, iron speciation, x-ray absorption spectroscopy.

Asbestos bodies (AB) are iron-rich coatings that form in vivo around inhaled asbestos fibres within lung tissue. Since the Fe-rich coating represents the actual interface between asbestos fibres and lung tissue, determining the chemical form of iron is crucial to understanding its role in the pathogenesis of asbestos-related diseases. Nevertheless, the speciation of Fe in AB remains debated. Ferrihydrite, the mineral phase storing Fe in the ferritin and hemosiderin core, is metastable and can transform into more crystalline phases such as goethite or hematite under specific environmental conditions (Bardelli et al., 2023).

This study investigates the iron speciation in AB to assess whether their composition is consistent across different samples, with the aim of gaining insight into possible patterns in their formation and associated toxicity.

The samples consist of non-neoplastic lung tissue fragments of former workers of a steel plant, an asbestos mine, and a textile mill. These individuals experienced prolonged exposure to different types of asbestos (primarily chrysotile, but also crocidolite and amosite) and developed asbestosis and/or pleural mesothelioma. We investigated the iron species constituting the AB using X-ray absorption spectroscopy (XAS) at the Fe K-edge, performed with synchrotron radiation. This technique allowed the detection of poorly crystalline phases such as ferrihydrite and enabled in situ analysis with high resolution. To explore compositional trends among the samples, we first applied principal component analysis (PCA), followed by linear combination fitting (LCF) to identify the iron phases. The results indicate possible variability in AB composition, with differing amounts of iron oxides and oxyhydroxides (ferrihydrite, goethite, and hematite). Synchrotron-based X-ray diffraction analyses on single AB are planned to confirm XAS results.

Bardelli F. et al. (2023) - Closing the knowledge gap on the composition of the asbestos bodies. Environ. Geochem. Health, 45(7), 5039-51, https://doi.org/10.1007/s10653-023-01557-0.

Sb and As removal from mining drainages by Layered Double Hydroxides (LDHs)

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Keywords: layered double hydroxides, Sb-As pollution, mine drainages.

Antimony (Sb) and arsenic (As) are recognized as Critical Raw Materials (CRM) by the European Union, due to their economic importance and supply risks for European countries. At the same time, Sb and As are highly toxic elements, listed as "priority pollutants" by the U.S. Environmental Protection Agency.

The concentrations of both As and Sb in natural unpolluted waters are typically lower than 1-10 µg L^{-1} but can significantly increase in areas affected by mining, processing and related activities. Waters flowing in the abandoned mine area of Su Suergiu (SW Sardinia) are interested by high concentrations of Sb (10^3-10^4 µg L^{-1}) and As (10^3 µg L^{-1}). These waters show Ca(Na)-sulfate chemical composition and are characterized by circum-neutral to slightly alkaline pH and oxidizing condition. In these conditions both Sb and As are stable in solution as oxyanions and can be dispersed for several km away from the source of pollution (Cidu et al., 2018; Fancello et al., 2023).

In the framework of the project PRIN-PNRR2022 (MOLIERE - antiMony resOurce itaLy envIronmental Exploration cRitical matErial), the removal of Sb an As by Layered Double Hydroxides (LDHs) has been investigated. LDHs are minerals with a layered structure with positive layers (brucite-like sheets ($[M^{2+}_{1-x}M^{3+}_{x}(OH)_2]^{x+}$)) alternated with negative ones ($[(A^{n-})_{x/n}]^{x-}\cdot mH_2O$) (Mills et al., 2012). These minerals can remove anionic pollutants in solution by either anion exchange in untreated LDHs, or incorporation in the interlayer during reconstruction of the structure after calcination (the so-called memory effect).

The capacity of LDH to remove Sb and As has been tested by batch and column experiments to assess the conditions (e.g. LDH composition, solid/solution ratio, initial pollutant concentrations, etc.) at which the removal is more efficient. For this purpose, LDHs were firstly tested with synthetic aqueous solution (obtained in laboratory by adding Sb and As to deionized water) to determine the removal efficiency. Subsequently, waters from slag drainages sampled in the abandoned mine area of Su Suergiu, under different seasonal conditions, were used to assess the effect of anion competition especially the carbonate species (up to 650 mg L^{-1}).

Acknowledgements: The research was founded by PRIN-PNRR2022 (MOLIERE - antiMony resOurce itaLy environmental Exploration cRitical material).

Cidu R. et al. (2018) - Fate of Antimony and Arsenic in Contaminated Waters at the Abandoned Su Suergiu Mine (Sardinia, Italy). Mine Water Environ., 37, 151-165, https://doi.org/10.1007/s10230-017-0479-8.

Fancello D. et al. (2023) - Antimony contamination sources and alteration pathways of Sb mineral phases in an abandoned mining area: The role of secondary mopungite [NaSb(OH)6]. Appl. Geochem.,156, 105764, https://doi.org/10.1016/j.apgeochem.2023.105764.

Mills S.J. et al. (2012) - Nomenclature of the hydrotalcite supergroup: Natural layered double hydroxides. Mineral. Mag., 76, 1289-1336.

Chemical and physical property modifications in hydrated cement induced by nano Mg-Al Layered Double Hydroxides (LDHs)

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Keywords: layered double hydroxide, cement hydration, anion binding capacity.

Ensuring the sustainability of cement production is essential for the future of the construction industry. One effective strategy to enhance sustainability is the incorporation of suitable additives into conventional cement formulations to improve durability. A thorough understanding of the physical and chemical mechanisms involved in the hydration of modified cements is therefore critical (Wu et al., 2021). Layered Double Hydroxides (LDHs) are promising candidates as cement additives due to their controllable supramolecular structures and unique physicochemical properties, such as anion exchange capacity. LDHs can capture CO_2, thus improving carbonation resistance, and remove harmful ions like Cl^- and SO_4^{2-} that could otherwise compromise cement durability. In this study, nano-sized Mg-Al-NO_3/$HCOO^-$ LDHs were synthesised using an ultrasound-assisted co-precipitation method. Their structures and morphologies were characterised by X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), dynamic light scattering (DLS), and Fourier-transform infrared spectroscopy (FTIR). The synthesised nano-LDHs were incorporated into Portland cement (CEM I) at varying weight percentages (1%, 3%, and 5% wt). The influence of LDHs on the early hydration behaviour of cement paste was investigated using in-situ XRD, differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA/DTG). These techniques provided insight into the chemical effects of LDHs on the formation of key hydration products, such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (AFm) phases and allowed exploration of potential anion exchange processes during hydration. Furthermore, ongoing anion binding tests are evaluating the enhancement of the cement paste's binding capacity due to LDH addition, with a focus on anion exchange mechanisms and the formation of compounds such as Friedel's salts. Mechanical tests (compressive strength measurements) were also conducted to assess the physical impact of LDHs on cement paste performance. The preliminary results presented here contribute to a deeper understanding of the role of selected nanomaterials in early cement hydration and durability. They also highlight possible adverse effects and support the optimisation of procedures for their effective incorporation into cement systems. The ultimate goal is to develop engineered cements with a reduced environmental footprint while meeting stringent physical and mechanical standards.

Acknowledgments: This work has been funded by the European Union – NextGenerationEU under the Italian Ministry of University and Research (MUR) National Innovation Ecosystem grant ECS00000041 - VITALITY - CUP J97G22000170005.

Wu Y. et al. (2021) - Role of layered double hydroxides in setting, hydration degree, microstructure and compressive strength of cement paste. Appli. Clay Sci., 158, 123-131, https://doi.org/10.1016/j.clay.2018.03.024.

Volcanic tuff and its uses as geopolymer precursor: advantages, characteristics, and case studies from the radioactive waste management sector

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Keywords: zeolite chabazite, geopolymers, radioactive waste management.

Geopolymers (GPs) emerged as promising cement substitutes in the field of radioactive waste management, in addition to their commonly investigated applications in the building industry. These novel binders are obtained by the reaction of an either alkaline or acid solution, the activator, with one or more aluminosilicate sources, the precursors. The resulting material, mostly amorphous, may offer elevated mechanical performances and resistance to chemically aggressive environments (Wang et al., 2019). Moreover, GPs are considered more environmentally friendly than ordinary cement, as precursors are often either industrial byproducts (e.g. coal fly ash, ground granulated blast furnace slag, electric arc furnace slag) and/or natural materials requiring moderate-to-none processing (e.g. kaolin, volcanic ash, zeolites). In the nuclear sector, GPs offer consistent advantages for the immobilisation of challenging radioactive wastes, such as spent ion exchange resins and liquid scintillation cocktails, overcoming some limitations of cement-based binders (Mossini et al., 2023; Galluccio et al., 2024). The proposed work aims at giving an overview on the use of a chabazite-rich volcanic tuff (VT) as GP precursor and filler. Other than being a natural and abundant material, this VT contains an elevated fraction of zeolite chabazite (about 65% w/w) which, thanks to its selective ion-exchange sites can be exploited to mitigate the diffusion of specific cations particularly important for radiological safety, most of all 137Cs+ (Baek et al., 2018). Different aspects coming from a selection of studies were highlighted:

(i) The effects of the type, concentration, and pH of the activator on the stability of the VT mineralogical phases. Particular focus will be put on the effects of using an acid activator, namely phosphoric acid, on the stability of chabazite and the resulting reaction products. (ii) Advantages of using VT as precursor in terms of reduced environmental impact, in particular when compared to other common options. (iii) Applications coming from radioactive waste management studies, such as the encapsulation of VT coming from the decontamination of liquid effluents containing 137Cs. The findings were corroborated by various characterisations, such as powder X-ray Diffraction, Thermogravimetric Analysis, and Scanning Electron Microscopy. Furthermore, compressive strength and leaching tests were carried out to evaluate the performance of the GPs according to the Waste Acceptance Criteria posed by the Italian regulator. The use of VT as GP precursor revealed to be advantageous for radioactive waste management applications, in particular regarding Cs immobilisation. Although chabazite easily degraded in acidic environment, these promising performances were also confirmed for phosphoric acid-activated GPs. Being environmentally friendly and highly versatile, VT is a promising material for radioactive waste management applications.

Baek W. et al. (2018) - Cation Exchange of Cesium and Cation Selectivity of Natural Zeolites: Chabazite, Stilbite, and Heulandite. Micropor. Mesopor. Mat., 264, 159-66, https://doi.org/10.1016/j.micromeso.2018.01.025.

Galluccio F. et al. (2024) - Pre-Disposal Management of Spent Ion-Exchange Resins by Fenton Oxidation Treatment and Conditioning in an Alkali-Activated Matrix. Nucl. Eng. Des., 429, 113621, https://doi.org/10.1016/j.nucengdes.2024.113621.

Mossini E. et al. (2023) - Pre-Impregnation Approach to Encapsulate Radioactive Liquid Organic Waste in Geopolymer. J. Nucl. Mater., 585, 154608, https://doi.org/10.1016/j.jnucmat.2023.154608.

Wang Y. et al. (2019) - Silico-Aluminophosphate and Alkali-Aluminosilicate Geopolymers: A Comparative Review. Front. Mater., 6, https://doi.org/10.3389/fmats.2019.00106.

Sicilian Skin Clays: mineralogical evaluation for the drug delivery aim

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Keywords: clay deposits, Sicily, pharmaceutical.

This study was developed with the aim to test innovative applications of Sicilian clays as delivery systems for bioactive compounds in pharmaceutical and cosmetic formulations. The idea stems from the need to valorise regional geo-resources through interdisciplinary approaches that combine mineralogical characterization with functional performance in advanced technological contexts. Sicily has a remarkable variety of sedimentary successions enriched in clay minerals, historically exploited for ceramic production. However, the potential of these clays for other applications, such as drug delivery, remains largely unexplored. At this purpose, four clayey deposits from eastern Sicily: two of these belong to the Varicoloured Clays Formation, CALT1 (green) and CALT2 (red), chosen for their high content of clay-sized particles; the other two samples: SIL, from Plio-Pleistocene deposits, and CEN, from the Terravecchia Formation, considered based on their wide geographic distribution and variable carbonate contents. Mineralogical analyses performed by X-ray diffraction (XRD) revealed complex assemblages consisting not only of phyllosilicates but also of non-clay minerals such as quartz, calcite and plagioclase. Complementary geochemical data obtained through X-ray fluorescence (XRF) and loss on ignition (LOI) showed a clear compositional distinction between the Varicoloured clays and the other samples, with the former characterized by higher concentrations of alumina and iron oxides and a notably low calcium content. Following granulometric separation to isolate the < 2 μm fraction, the samples were converted into Mg monocationic forms in preparation for functional testing. Additional mineralogical analyses on the clay fractions revealed the presence of smectite, interlayered illite/smectite (I/S), kaolinite, illite/chlorite. The green Varicoloured clay (CALT1) exhibited a predominance of I/S with R1 ordering (I/S75), along with kaolinite and chlorite, while the red variety (CALT2) contained I/S80 R1 and kaolinite. In contrast, the SIL and CEN samples were dominated by smectite, I/S with R0 ordering and kaolinite. FT-IR spectroscopy revealed a common absorption at ~3620 cm^{-1}, attributed to internal hydroxyl groups in all clay samples. The distinct band at 3695 cm^{-1}, more evident in SIL and CEN, indicates higher kaolinite content, as it corresponds to Al–OH stretching vibrations. Conversely, CALT 1 and CALT 2 exhibit stronger signals linked to smectite, suggesting a more hydrated clay composition. The observed differences in the clay minerals assemblages reveals diverse geological context and diagenetic conditions. To assess the clays' performance as delivery systems, resveratrol, a natural polyphenol with known anti-inflammatory and anti-psoriatic properties, was used as a reference bioactive compound. The encapsulation process did not significantly alter the structural properties of the clays, indicating their stability and compatibility.

Alkaline activated materials as consolidants for the conservation of historic mortars

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Keywords: alkaline activated materials, consolidation, injectability.

Consolidation of disintegrated mortars is a critical challenge in the field of restoration, which must ensure structural stability and preserve the authenticity of original materials. Injection techniques represent an effective solution to stabilise incoherent substrates, but their efficiency depends on the characteristics of the injected material (Biçer-Simsir & Rainer, 2013). This research examines the suitability of alkali activated materials developed for this purpose. Obtained by chemical reactions between aluminosilicate precursors and alkaline activating solutions, alkaline activated materials are characterised by high mechanical performance and reduced environmental impact. Furthermore, by modifying alkaline activators and the liquid/solid ratio, it is possible to tailor important properties such as fluidity and curing time, and thus workability and applicability (Koutnik et al., 2020), two fundamental aspects for intervention in consolidation. Natural geomaterials and industrial by-products, particularly metakaolin and fly ash, are used - solely or in binary mixtures - to develop various formulations with sodium- and potassium-based activators that have the capacity to be injected in columns filled by loose aggregates, simulating deteriorated mortars. Assessed their chemical stability and the good mechanical performances, the differences in penetrative ability through loose aggregates and the rheological behavior of the formulation at varying liquid/solid ratio and at varying time were studied. The obtained preliminary results highlight critical points linked to the tendency of some formulation to phase separation or sedimentation, and so the necessity to use additives to improve the performance during application. On the other side, preferable formulations have been individuated, which show at the same time good injection application and good microstructural characteristics and cohesive properties. Applicative tests performed directly on site, at the Benedictine Monastery of Catania, are also shown.

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Biçer-Simsir B. & Rainer L. (2013) - Evaluation of lime-based hydraulic injection grouts for the conservation of architectural surfaces. The Getty Conservation Institute, Los Angeles, 105 pp.

Koutnik P. et al. (2020) - Low viscosity metakaolinite based geopolymer binders. Constr. Build. Mater., 230, 116978, https://doi.org/10.1016/j.conbuildmat.2019.116978.

Industrial ceramic manufacturing: minero-petrographic characterisation of commercial tiles and experimental ceramic samples for the determination of quality indicators

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Keywords: industrial ceramic tiles, minero-petrographic analysis, performances.

This research focuses on the characterization of commercial ceramic tiles and experimental ceramic samples from a minero-petrographic and technological point of view to identify performance parameters and defects. Samples of industrial tiles and various raw materials were supplied by Gruppo Ceramiche Gresmalt S.p.A., a leading company in the ceramic sector. This company is also leading a project called START (https://www.start-innovability.it/), Sustainable Data-driven Manufacturing, funded by the Ministry of Enterprises and Made in Italy, aimed at researching and validating technological solutions for digital transformation and product optimization. The study analyzed the samples to support the project's objective of developing predictive and classification models for the quality of ceramic materials using machine learning and feature extraction techniques. Various analytical methods have been used, including optical microscopy, X-Ray diffractometry, scanning electron microscopy and electron microprobe analysis, to characterize the tiles from mineralogical, petrographic and chemical perspectives. Water absorption and linear shrinkage (after firing) tests were also carried out to evaluate their performance characteristics. The results indicate that commercial tiles mainly have some structural differences, despite controlled production processes. Analytical techniques have revealed microdomains and microstructures within the tiles that can cause defects. The experimental ceramic samples showed slight differences due to variations in the composition of the used raw materials and in the production conditions (mainly firing temperature). Water absorption tests have highlighted the importance of process parameters to ensure the compactness and strength of the product. In summary, the research provides preliminary insights into the technological aspects of ceramic production, linking them to defects and performance, which can improve the optimization of production processes.

Novel Mayan-inspired hybrid composites obtained by complexing lawsone and methyl orange to palygorskite: structural features and applications

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Keywords: palygorskite, hybrid composite, host/guest interactions.

Novel hybrid composites, heavy metals-free and apt to be used for sustainable applications, can be prepared by grinding and heating different guest dyes on palygorskite – a fibrous, microporous clay mineral, strictly following the ancient recipe used to prepare the famed Maya Blue pigment (Giustetto & Wahyudi, 2011).

The structural features and physical/chemical properties of such composites obtained with lawsone and methyl orange are investigated here, by using a multi-analytical protocol (including SEM-EDS, BET-SSA, UV-vis and ATR-FT-IR spectroscopies) to check their stability and study the nature of the mutual (if any) host/guest interactions.

When complexed to palygorskite, Lawsone forms a stable adduct thanks to specific H-bonds established between the C=O groups and the structural/zeolitic water in the surface grooves of the clay fibrils. Such an achieved stability and sensitivity to pH fluctuations (yellow in acids; orange in alkalis) suggests that this composite might potentially be used as either a solid-state acid/base indicator and colorimetric-electrochemical sensor for anions, or for pollutants bio-reduction in remediation activities.

On the other hand, methyl orange undergoes systematic degradation when heated on palygorskite, forming derivatives unable of efficiently binding to the host framework. Despite a presumed affinity of palygorskite for absorbing azo dyes (Giustetto et al., 2014, 2017), stabilization does not occur for methyl orange, the clay framework being unable to shield the dye molecule.

Giustetto R. & Wahyudi O. (2011) - Sorption of red dyes on palygorskite: Synthesis and stability of red/purple Mayan nanocomposites. Micropor. Mesopor. Mat., 142, 221-235, https://doi.org/10.1016/j.micromeso.2010.12.004.

Giustetto R. et al. (2014) - Evolution and Reversibility of Host/Guest Interactions with Temperature Changes in a Methyl Red@Palygorskite Polyfunctional Hybrid Nanocomposite. J. Phys. Chem. C., 118, 9322-19337, https://doi.org/doi.org/10.1021/jp4091238.

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Tuff waste from Riano (Lazio) shows new technological insights by paving the road towards an eco-friendly reuse

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Keywords: zeolites, tuff waste, eco-friendly reuse.

The green economy, in the context of industrial production, focuses on the sustainable use of resources and waste, with the goal of reducing environmental impact through recycling, reuse, and valorization of natural and man-made geomaterials. This means increasing energy efficiency, reducing waste, and moving toward a circular economy.

It is easy to imagine that industrial processing wastes pose a logistical and environmental problem, as they require precise regulations and treatment for disposal/storage. Waste from the processing of geomaterials is no exception to these concepts, and although it may be contaminated to some extent by the processing itself or by the wear and tear of industrial tools (abrasive parts of cutting tools such as circular saws and discs or polishing powders and abrasive pastes), it still retains all the main mineralogical and compositional characteristics of the original material. Under these assumptions, a waste deriving from the cutting and processing operation to produce dimension stones of a volcanic tuff deposit (Tufo giallo della via tiberina) in Riano (Lazio) containing authigenic (feldspars) and secondary mineralization (zeolites, mainly chabazite and subordinate phillipsite and analcime; Cappelletti et al., 1999) can be considered as a useful by-product for industrial applications in different sectors.

This study presents preliminary results of the characterization of these wastes. Results show the possible reuse in different technological applications: production of lightweight aggregates, pharmaceutical support and environmental pad for emerging contaminants (Mercurio et al., 2019, and references therein), pozzolanic addition in cement or partial replacement of feldspathic fluxes (Graziano et al., 2024, and reference therein). The experimental procedures used in this study with the waste from the Riano tuffs can be safely extended to other similar materials, representing a potential circular alternative to landfill disposal.

Cappelletti et al. (1999) - Mineralogical and technical features of zeolite deposits from northern Latium. Period. Mineral., 68(2), 127-144.

Mercurio M. et al. (2019) - Modified clay and zeolite nanocomposite materials. Environmental and pharmaceutical applications. Micro & Nano Technologies Series. Elsevier, 343 pp., https://doi.org/10.1016/C2017-0-01250-8.

Graziano S.F. et al. (2024) - A recycled natural resource as secondary raw material for versatile technological applications: the quarry waste from zeolite-rich tuffs. Appl. Clay Sci., 258, https://doi.org/10.1016/j.clay.2024.107451.

Zeolites performance investigation in the adsorption of heavy metals from MSWI fly ash leachates

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Keywords: PFAS, soil, zeolites.

This work examines the use of natural and synthetic zeolites (5A, 13X, Y720, and CHA) as functional materials for the retention of heavy metals present in leachates derived from the steam washing of Municipal Solid Waste Incineration (MSWI) fly ash (Destefanis et al., 2020; Bernasconi et al., 2025). Through batch adsorption experiments, the capacity of each zeolite to remove metals such as Pb, Zn, Cd, Cu, Mn, and Fe was systematically compared. Zeolite 13X emerged as the most efficient, particularly in removing Pb, Zn, and Cu, a result linked to its large pore volume and favorable framework geometry. Zeolite 5A also performed well with Zn and Pb, while Zeolite Y720 showed a preference for Mn and Fe, likely influenced by its elevated Si/Al ratio, which enhances selectivity toward certain cations. CHA-type zeolite demonstrated moderate efficiency for Pb and Zn, though its performance was affected by the presence of competing ions such as Ca, K, and Mg. The study emphasizes the role of structural features, such as pore topology, cation exchange capacity, and framework composition in controlling adsorption behavior, and suggests tailored zeolite selection as a key strategy for sustainable treatment of hazardous waste leachates.

Bernasconi D. et al. (2025) - Steam washing for MSWI-FA treatment. Waste Manage., 195, 10-21.

Destefanis M. et al. (2020) - Steam washing for incinerator residue treatment: Improving leaching efficiency and metal recovery. Waste Manage., 104, 1-8.

Dololime and Mg-base lime synthesis for FGD application

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Keywords: dololime hydration, Mg-lime hydration, flue-gas desulphurization absorbers.

The development and validation of advanced methodologies for assessing lime hydration is presented in this study, employing a newly engineered, fully integrated planetary mixer tailored for Cimprogetti's Technological Laboratory. This specialized equipment ensures consistent hydration across a broad spectrum of light- and hard-burned materials, including high-calcium lime (quicklime), magnesium-enriched lime (dololime), and Mg-based lime (periclase).

The principal objective is to achieve complete hydration, even in low-reactivity compounds, thereby producing end products with high specific surface area and pore volume (PV), suitable for a range of industrial applications, especially acid neutralization and flue-gas desulphurization (FGD). To this end, a series of optimized hydration protocols were established to synthesize enhanced double-hydrated dololime, and magnesium hydroxide. These were produced from laboratory-calcined pure dolomite and magnesite rocks of diverse geological origins, simulating various industrial kiln outputs. It is well-established that firing conditions critically influence the reactivity of the resulting Ca-Mg oxides with water (Vola et al., 2019; consequently, hydration efficiency is strongly affected by the degree of overburning or sintering, often associated with increased crystallite size. Notably, the complete transformation of periclase (MgO) into brucite ($Mg(OH)_2$) in dolomitic lime is difficult to achieve under ambient conditions (Lanas & Alvarez, 2004) and, sometimes, even under elevated temperature and pressure (Tang et al., 2014).

High hydration temperatures (70-130°C) and medium-high pressure (~3 bar self-generated during reaction) were employed to overcome this challenge. This approach facilitates the synthesis of specialized hydrated products for acid gas treatment through custom formulations, including high water-to-lime ratios and the addition of triethanolamine (TEA) as a grinding and dispersing aid.

An extensive characterization of both pre- and post-hydration materials was conducted by X-ray powder diffraction analysis (XRPD). Whole pattern profile fitting performed by the Rietveld method allowed performing the microstructural analysis, i.e., crystallite-size and microstrain determination, and the quantitative phase analysis. Complementary density and porosity measurements were carried out using nitrogen gas pycnometry and adsorption techniques. In particular, specific surface area, pore size, and pore diameter were evaluated via BET and BJH methods, respectively. The synthesized materials demonstrate significant potential for deployment in intended industrial applications.

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Tang X. et al. (2014) - The analysis of magnesium oxide hydration in three-phase reaction system. J. Solid State Chem., 213, 32-37, https://doi.org/10.1016/j.jssc.2014.01.036.

Vola G. et al. (2019) - Reactivity and overburning tendency of quicklime burnt at high temperature. Cimprogetti Srl Lime Technologies, www.zkg.de.

The path of Phlegraean pozzolana: from Puteoli to the whole Mediterranean basin

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Keywords: pozzolana, mortars, romans.

Phlegraean pozzolana, called "pulvis puteolana" by M. Vitruvius Pollio in his famous "De Architectura" (I century B.C.) book, used to play an important role to produce Roman hydraulic mortars, capable of enhancing mechanical strength even in underwater conditions. This geomaterial was widely employed by Romans, as it has been found in different locations across the Mediterranean basin (ROMACONS Project, Oleson et al., 2004).

This study investigates the provenance of pozzolana used in Roman mortars by comparing different pozzolana samples collected from quarries in the Campi Flegrei area, which were historically well known by Romans, with pozzolanic aggregates found in hydraulic mortars from both Campanian archaeological structures and extra-regional sites such as Venice (Dilaria et al., 2024), Aquileia (UD) (Dilaria et al., 2023b), the Temple of Nora in the Sardina region (Dilaria et al., 2023a) and Soli Pompeiopolis in Turkey (Stanislao et al., 2011).

The pozzolana samples were analyzed using a multi-analytical approach, to obtain chemical and minero-petrographic information through Polarized Optical Microscopy (POM), X-Ray Powder Diffraction (XRPD), Field Emission Scanning Electron Microscopy coupled with Energy-Dispersive X-Ray Spectroscopy (FESEM-EDS) and Laser Granulometry.

By comparing mineralogical and chemical results of the analyzed samples with the literature data regarding the ancient mortars pozzolanic aggregates, this research presents preliminary results aiming to understand if there are compositional differences among aggregate fractions found in mortars from different sites and, eventually, if there was a preference regarding the exportation of a pozzolana from specific location.

This research could serve as a reference database to further our knowledge of ancient Roman technology.

Dilaria S. et al. (2023a) - Volcanic Pozzolan from the Phlegraean Fields in the structural mortars of the Roman temple of Nora (Sardinia). Heritage, 6(1), 567-586.

Dilaria S. et al. (2024) - Vitruvian binders in Venice: First evidence of Phlegraean pozzolans in an underwater Roman construction in the Venice Lagoon. PloS one, 19(11), e0313917.

Dilaria S. et al. (2023b) - Early exploitation of Neapolitan pozzolan (pulvis puteolana) in the Roman theatre of Aquileia, Northern Italy. Scientific Reports, 13(1), 4110.

Oleson J.P. et al. (2004) - The ROMACONS Project: A contribution to the historical and engineering analysis of hydraulic concrete in Roman maritime structures. International Journal of Nautical Archaeology, 33(2), 199-229.

Stanislao C. et al. (2011) - Contribution to the knowledge of ancient Roman seawater concretes: Phlegrean pozzolan adopted in the construction of the harbour at Soli-Pompeiopolis (Mersin, Turkey). Periodico di mineralogia, 80(3), 471-488.

Italian natural zeolites as promising georesource: from sawing waste to “strategic” minerals

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Keywords: natural zeolites, functionalization, exploitation.

Natural zeolites are versatile and technologically viable minerals which positively predispose them to the social tasks of the near future. Growing environmental concern, innovative drug development, the green deal, and organic farming represent some of these challenges. Little is being done to promote these minerals on the European scale despite Slovakia is the world’s leading producer of natural zeolites (exporting clinoptilolite-rich deposits; USGS, 2025). In contrast, the Asian region has been more forward-looking and to date boasts an ever-growing use despite the fact that it is known to have no large deposits to exploit. This is setting the stage for pushing toward the use of Italian zeolitized deposits, which are abundantly present on the perithyrrhenian margins of the peninsula characterized by the occurrence of volcanic and volcanoclastic deposits, with high concentration (sometimes reaching more than 50 %wt., and thus able to be defined zeolitites) of zeolites minerals such as: chabazite and phillipsite (Tuscany, Latium and Campania regions) and in smaller quantities of clinoptilolite (Sardinia). The debate that is brewing, however, reveals a major problem. Italian legislation managing natural resources may be considered anachronistic. In fact, it dates back to the beginning of the last century when the technological potential of this georesource was unknown to all. Although limited the exploitation of natural Italian zeolite-rich geomaterials has been possible because they were considered a waste deriving from the production of bricks for the construction sector, so far. A very limited use compared to the potential available resource. Actually, over the past 15 years some natural Italian zeolitites have been characterized and explored for more technologically advanced uses thus proving to be suitable, further than the well-known cation exchange, also to exchanging oxyanions and organic molecules after surface functionalization. Such a new complementary approach aiming at investigating novel properties of these georesources sheds new light on the possible real and potential applications that lie ahead. Therefore, based on the above considerations, it becomes essential to promote these technologically viable minerals also through a series of actions aimed at: i) amending the Italian law dealing with this matter, ii) promoting at the European scale the use of this georesource taking into account the quantities available and the economic implications of such a targeted exploitation, and iii) deepening at the industrial scale some uses that are currently supported only by robust laboratory tests (Mercurio et al., 2018, 2019; Graziano et al., 2024). Such a novel strategy could hopefully remedy the market distorsions that, to date, sees Cuban zeolites (mordenite-rich materials?!) being imported into Italy for massive use in agriculture. The aim of this work is to overcome this evident paradox.

Graziano S.F. et al. (2024) - A recycled natural resource as secondary raw material for versatile technological applications: the quarry waste from zeolite-rich tuffs. Appl. Clay Sci., 258, 107451, https://doi.org/10.1016/j.clay.2024.107451 .

Mercurio M. al. (2018) - Surface-modified phillipsite-rich tuff from the Campania region (southern Italy) as a promising drug carrier: An ibuprofen sodium salt trial. Am. Mineral., 103, 700-710, https://doi.org/10.2138/am-2018-6328.

Mercurio M. et al. (2019) - Modified clay and zeolite nanocomposite materials. Environmental and pharmaceutical applications. Micro & Nano Technologies Series. Elsevier, 343 pp., https://doi.org/10.1016/C2017-0-01250-8.

USGS (2025) - Zeolites statistics and information, annual publications. U.S. Geological Survey, Mineral Commodity Summaries, https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-zeolites.pdf.

Zeolites as ceramic raw materials for feldspar substitution in porcelain stoneware tiles production

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Keywords: zeolitized tuff, porcelain stoneware, technological properties.

In recent years, there has been a growing trend in the demand for white-firing clay materials for ceramic tile production, following a continued shift towards porcelain stoneware bodies. The sourcing of raw materials by industries on the global scene has been challenged by the current geopolitical scenario, consequently requiring a rethink of the well-established European supply chain, and there is an urgent need to evaluate the possibility of using Italian raw materials to produce porcelain stoneware. With this in mind, zeolite-containing waste generated from extraction and processing tuffs (ZT) from two active quarries in Sorano (Tuscany, Italy) were studied. The experimental work was carried out to characterize and test ZT as feldspars substitute in porcelain stoneware formulation. Collected samples were physically and chemically characterized and the most promising material was defined on the base of thermal stability (lower bloating). Two different amounts were tested (10-20 wt%) for feldspars substitution in comparison with a reference porcelain stoneware batch and tile-making process was replicated at the laboratory scale. Samples were characterized in terms of technological properties throughout the process. Waste addition led to a limited reduction of green and dry bulk density, not followed by a decrease in mechanical properties. All the studied batches show a maximum in linear shrinkage and bulk density at 1200°C, reaching the standard requirement for water absorption and mechanical properties. For mixture with 20 wt% waste addition, the desired values are reached already at 1180°C leading to reduce thermal energy demand. On the basis of the achieved results, the use of ZT is suitable in the whole evaluated range selected for porcelain stoneware production and to be screened for a potential industrial scale up.

The legacy of Roman technology: a window into the past for future constructions

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Keywords: roman mortars, pozzolana.

Technological advances throughout history have been achieved through the wise and intensive use of available georesources. Mortars are composite geomaterials (i.e., geological natural materials or deriving from technological transformations of geological materials) consisting of hydraulic or aerial binder, aggregates and additives reacting with binder and undergoing modifications during setting (Moropolou et al., 2005). The use of pozzolan marked a great advance in construction technology since Roman Age: ancient pozzolanic mortars testify the high technological quality achieved by Roman construction workers, due to their excellent preservation state in every environment. The original pozzolan is the pulvis puteolana, a volcanic sand from the Phlegraean Fields area. As reported by Vitruvius, this was considered a "prodigious powder" outcropping in a wide region, from Baia and Cumae to Vesuvius and Sorrento Peninsula. The Romans founded one of the greatest empires in history, conquering the Mediterranean area and half of Europe. The sign of their passage can be seen through buildings, roads, aqueducts, temples and monuments. From an architectural perspective, the Romans inspired many populations, both past and present. Their ability to build monuments starting from simple geological materials and obtaining more complex ones that would last over time has been, and still is, object of interest for researchers.The study of Roman mortars holds exceptional significance for understanding the advanced construction technologies employed by ancient builders. The preservation state of these geomaterials, many of which have endured for millennia, testify the very high technical expertise and craftsmanship of Roman builders. The manufacturing technology developed by the Romans were truly innovative, emphasizing not only structural strength but also quality, sustainability, longevity, and aesthetic appeal. Their approach integrated natural materials such as pozzolan, which enhanced the hydraulic properties and resilience of mortars, enabling the construction of enduring architectural operas. Nowadays, valuable insights from Roman techniques can be drawn to develop sustainable building materials that balance durability with environmental responsibility. Therefore, contemporary constructions can benefit from time-tested methods that promote longevity and beauty while reducing environmental impact. In essence, the legacy of Roman technology is not only a window into the past but also a source of inspiration and practical knowledge for the future of construction and material science.

Moropoulou A. et al. (2005) - Composite materials in ancient structures. Cem. Concr. Compos., 27, 295-381, https://doi.org/10.1016/j.cemconcomp.2004.02.018.

Sustainable synthesis of layered double hydroxides via sonochemical and mechanochemical routes

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Keywords: layered double hydroxides, green synthesis, sonochemical-mechanochemical synthesis.

Layered double hydroxides (LDHs) with general formula $[M(II)_{1-x}M(III)_x(OH)_2](A^{-n})_{x/n}\cdot mH_2O$, were M(II) is a divalent cation (i.e. Zn, Mg, Cu, Co), M(III) a trivalent cation (i.e. Al, Ga, Fe) and An- the anions that balance the positive charges of the lamellae, have attracted great interest thanks to the great variability of the intra- and interlayer composition. Catalytically active metal ions can be used as a component of the layer or immobilized on its surface after creating defect sites. These materials can be used as catalysts or catalyst precursors to promote water splitting (Sahoo et al., 2022), Fischer-Tropsch reaction (Grainca et al., 2024), biomass conversion (Wu et al., 2023). More recently, new application of LDH has been envisaged as additive material in cement and concrete production to improve their durability (removing harmful ions like Cl^- and SO_4) and increasing compressive strength.

All of these applications at an industrial level can be realized through the implementation of green and scalable synthesis methods. Therefore, the possibility of producing LDH and modulating their layer composition and particle size using sustainable synthesis methods (especially in terms of production time and environmental costs) is a task to be pursued. In this communication, the synthesis of LDH by ultrasonic and mechanochemically assisted procedures, considered as emerging green and powerful syntheses, is reported and the results are compared with those obtained by a conventional method such as the precipitation at high supersaturation. LDH containing M(II) as Mg, Cu, Zn, Ni, Co and M(III) as Al, Ga, Fe have been prepared by different methods and compared in terms of composition, phase purity, and particle dimensions. Furthermore, the effect on the reactivity of LDH prepared by different methods has been studied for NiFe LDH, evaluating their catalytic performance as electrocatalysts for the oxygen evolution reaction (OER). These materials have been investigated for OER in alkaline media with various electrochemical measurements using a single compartment three electrode cell.

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Grainca A. et al. (2024) - Sonochemical and mechanochemical synthesis of iron-based nano-hydrotalcites promoted with Cu and K as catalysts for CO and CO_2 Fischer-Tropsch synthesis. Fuel, 373, 132303.

Sahoo D.P. et al. (2022) - Recent progress in first row transition metal Layered double hydroxide (LDH) based electrocatalysts towards water splitting: A review with insights on synthesis. Coord. Chem. Rev., 469, 214666.

Wu J. et al. (2023) - Confinement engineering, microenvironment effect and applications in catalytic conversion of biomass. Coord. Chem. Rev., 497, 215437.

Sustainable clay formulations and their feasibility in the ceramic roof tile industry: applications and resistance against freeze-thaw cycles

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Keywords: sustainable economy, frost action, ceramics.

Sustainability and Circular Economy have gained priority among the issues of modern industry, especially in activities that involve the extraction of raw materials from natural sources, i.e. clay quarries. The Italian ceramic industry plays an important role in this scenario, blending sustainable approaches with technological innovation. This project investigates various batches of ceramic roof tiles produced by an Italian company, whose performance does not align with the frost resistance tests performed in the laboratory. The action of frost often represents a significant issue in humid and cold climates. Fired clay-based materials that absorb water are subject to superficial exfoliation and loss of mechanical strength when temperatures fall below 0°C. This phenomenon, influenced by the raw materials' physical and mechanical properties (i.e. porosity), by the industrial manufacturing process, and by the design and construction of the roofing system, can compromise the service life of the finished product. In some cases, materials that are guaranteed to last up to 30 years have shown signs of delamination after only four years of exposure to the elements.

The aim of the project is to understand the reason behind this inconsistency, paying particular attention to clay mixtures containing 5% of recycled material and how it changes the performance of the finished product. The initial phase of the research involves the study of the mineralogical composition of the fired materials through XRPD analysis, as well as analyzing their porosity distribution by means of Image Analysis of thin sections, MIP and BET methods. Further analyses will explore the microstructure and the internal stresses of the tiles using the X-Ray Microtomography and 3D Image Analysis.

Mineralogical features and technological potential of colourful volcanic tuffs from Armenia

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Keywords: volcanic tuffs, multianalytical approach, geomaterials.

This study focuses on the mineralogical, petrographical, and technological characterization of several volcanic tuffs from Armenia, to explore their potential applications in industrial and high-value technological sectors. The geological settings of Armenia have been strongly influenced by volcanic activity, which led to the emplacement of a variety of pyroclastic deposits. Among these, tuffs certainly deserve particular attention, because, thanks to their physical and mechanical properties (Pötzl et.al., 2018), they have been used as building stones also in cultural heritage.

Moreover, due to their chemical and mineralogical properties, these materials, are potentially suitable for advanced technological applications as well as use for industrial processes that require inert supports or specific adsorption capabilities. To identify the potential field of application a comprehensive multi-analytical approach.is mandatory.

A multianalytical approach was used, integrating several techniques such as Optical Microscopy (OM), X-ray Powder Diffraction (XRPD), Field Emission Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (FESEM-EDS), Thermogravimetric (TG) analyses, Mercury Intrusion Porosimetry (MIP), and Pozzolanicity test (UNI EN 196-5:2011). The integration of the data obtained from these techniques allowed to draw a comprehensive and detailed profile of the textural, chemical, mineralogical, and physical-mechanical properties of the analyzed samples. The analyses revealed significant differences in the internal structure and texture of the tuffs, which directly influence their mechanical properties, durability and resistance to alteration. In particular: a) mineralogical, petrographic and chemical analyses revealed a composition dominated by crystalline phases such as plagioclase, alkali feldspar and clinopyroxene along with amorphous phase. It is worth noting the presence of cristobalite, even if detected only in one sample, as it is particularly significant for understanding post-depositional processes; b) thermal analyses allowed to assess the stability of the mineral phases as temperatures change; c) porosimetric data reveal a clear predominance of macropores, a feature that significantly affects the stone mechanical strength, water absorption, and long-term durability in construction applications; d) Pozzolanicity test indicated the potential suitability of the tuffs as reactive materials in combination with hydraulic binders, opening up interesting prospects for their use in the construction industry.

In conclusion, this study enhances the current knowledge on Armenian volcanic tuffs, including evidence of possible secondary devitrification processes affecting the original glassy matrix. These findings not only improve the understanding of the mineralogical evolution of these materials but also provide a scientific basis for evaluating their industrial and technological potential.

Pötzl C. et al. (2018) - Deterioration of volcanic tuff rocks from Armenia: Constraints on salt crystallization and hydric expansion. Environ. Earth Sci., 77, 660.

UNI EN 196-5 (2011) - Metodi di prova dei cementi: prova di pozzolanicità dei cementi pozzolanici.

Confirming the potentials of an Italian, chabasitic tuff in the management of radioactive Cs-bearing waste streams: a physical-chemistry investigation

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Keywords: chabasitic tuff, caesium, radioactive waste management.

Caesium plays a critical role in radioactive waste management due to the high mobility of Cs^+ ions: Cs forms volatile compounds and is easily leached from traditional encapsulation matrices, while the decay of Cs-137 generates heat, further challenging its confinement (Mukiza et al., 2024). Conventional coagulation and filtration are ineffective for Cs removal from effluents, while zeolites have proven highly effective, alongside materials like Prussian blue and metal-organic frameworks. Similarly, immobilization methods using cementitious alkalinated and geopolymeric binders, combined with zeolitic fillers, have shown promising results through chemical binding and structural incorporation of Cs (Misaelides et al., 2018).

In this work, a physico-chemical study on the interactions of Cs^+ ions with an Italian, chabasitic tuff was carried out. Owing to its natural origin, ready availability, low costs, and minor environmental footprint, this tuff has been the subject of previous investigations in the field of radioactive waste management, which had demonstrated its compatibility with alkali-activated and geopolymeric binders (Santi et al., 2022), and confirmed its positive impact on the lixiviation behaviour of Cs-bearing waste forms (Galluccio et al., 2024). For the purposes of this work, the tuff was preliminarily characterized by X-ray powder diffraction, scanning electron microscopy and elemental chemical analysis, confirming a 65 wt.% chabazite content. Kinetics tests showed that the tuff rapidly interacts with the simulated waste: under the tested conditions, 80% of the Cs^+ ions is removed after only 4 h of contact, while thermodynamic equilibrium is reached at 100 h. The sorption kinetics of Cs^+ ions follows a fourth-order kinetics, consistently with the presence of multiple competitive interaction mechanisms attributable to the tuff mineralogy. In agreement with the literature on nearly-pure chabazite, the sorption isotherm curves confirm the selectivity of the tuff toward Cs^+ ions and follow the Langmuir adsorption equation. Modelling the sorption as ion exchange reactions, it was possible to calculate the values of the equilibrium constant values, from which it was possible to derive the values of ΔH, ΔS and ΔG via the van't Hoff and Gibbs-Helmholtz equations. For temperatures between 10°C and 90°C, typical of many Cs-bearing industrial effluents, ΔG values are negative, indicating spontaneous fixation of the Cs^+ ions onto the tuff. Eventually, the selectivity of the tuff for the removal of Cs was confirmed in competitive conditions with a more representative simulant solution containing activation and fission products commonly found in low- and intermediate-level waste streams. Thanks to the results of this work and the previous proof of the compatibility of the tuff with the aluminosilicate binders, the potentials of the application of the chabasitic tuff to more straightforward management of Cs-bearing waste streams are confirmed.

Galluccio F. et al. (2024) - Pre-disposal management of spent ion-exchange resins by Fenton oxidation treatment and conditioning in an alkali-activated matrix. Nucl. Eng. Des., 429, 1-11, https://doi.org/10.1016/j.nucengdes.2024.113621.

Misaelides P. et al. (2018) - Investigation of chabazitic materials as Cs-137 sorbents from cementitious aqueous solutions. Micropor. Mesopor. Mat., 266, 183-188, https://doi.org/10.1016/j.micromeso.2018.02.048.

Mukiza E. et al. (2024) - Recent advances in immobilization of radioactive cesium and strontium-bearing wastes in alkali activated materials – A review. J. Environ. Manag., 370, 1-28, http://dx.doi.org/10.1016/j.jenvman.2024.122746.

Santi A. et al. (2022) - Design of sustainable geopolymeric matrices for encapsulation of treated radioactive solid organic waste. Front. Mater., 9, 1-17, https://doi.org/10.3389/fmats.2022.1005864.

Cobalt removal from contaminated solutions through synthetic AMC carbonates

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Keywords: cobalt, water, AMC carbonate.

Heavy metals (HMs, i.e., Pb, Cd, Ni, Co, Zn, Cu, etc.) represent the most hazardous pollutants in water and soils due to their high toxicity for human health and negative impact on biological systems (Nagajyoti et al., 2010). Cobalt pollution of water and soil is related to industrial activities such as electroplating and can be significantly intensified by mining activities, resulting in Co concentrations in the environment considerably higher than regional background levels (Leyssens et al., 2017; Zhang et al., 2018; Mahey et al., 2020). Sustainability and waste management are keywords in the remediation actions of HMs-wastes for EU policy. Moreover, low-cost and performant methods for waste treatment are prerequisites for sustainable development, environmental remediation, and human health. This study investigated the efficiency of Co removal from solutions using Mg-carbonates, previously synthesized through a mineralization process involving the interaction of gaseous CO_2 with $MgCl_2$ solutions. Amorphous Mg-carbonates (AMCs) are an optimal solution/sink for removing Co from solutions, as their open structure facilitates ion exchange between Mg and Co. Solutions with concentrations of Co 50, 100, 150, 250, 500, and 1000 mg/L were prepared using cobalt nitrate hexahydrate as the starting material. All removal experiments have been performed at room pressure and temperature, considering 9 increasing interaction times with AMCs (ranging from 20 minutes to 4 weeks). AMCs were characterized using SEM-EDS, XRPD, and FTIR analysis of solid materials. The residual solutions were analyzed using ICP-AES to assess the extent of Co removal and process efficiency; the removal capacity (qe) and removal percentage (R%) were calculated from this data. Across all experiments conducted so far, SEM-EDS analysis showed progressive morphological changes in AMCs and an increase in Co content with contact time. XRPD results demonstrated a transformation of the AMC lattice into a hydrated Co-carbonate structure, with near-complete substitution of Mg by Co. The Co removal percentage (R%) was about 75%, and the removal capacity (qe) ranged between 373 and 378 mg/g for the concentration of 1000 mg/L of Co. The study suggests that the proposed methodology could be an efficient solution for treating water contaminated by heavy metals and reducing CO_2 emissions.

Leyssens L. et al. (2017) - Cobalt toxicity in humans - A review of the potential sources and systemic health effects. Toxicol., 387, 43-56, https://doi.org/10.1016/j.tox.2017.05.015.

Mahey S. et al. (2020) - A critical review on toxicity of cobalt and its bioremediation strategies. SN Appl. Sci., 2, 1279, https://doi.org/10.1007/s42452-020-3020-9.

Nagajyoti P.C. et al. (2010) - Heavy metals, occurrence and toxicity for plants: a review. Environ. Chem. Lett., 8, 199-216, https://doi.org/10.1007/s10311-010-0297-8.

Zhang R. et al (2018) - Effective removal of toxic heavy metal ions from aqueous solution by $CaCO_3$ microparticles. Water Air Soil Poll., 229, 1-14, https://doi.org/10.1007/s11270-018-3787-0.

From Roman knowledge to conservation of Built Heritage: advances in sustainable pozzolanic mortars

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Keywords: pozzolanic mortars, advanced admixtures, conservation strategies.

The integration of natural pozzolanic materials into Roman mortar formulations represents a remarkable milestone in ancient construction technology. Volcanic sands from the Somma-Vesuvius area, in particular, played a key role in the production of hydraulic mortars, enabling the development of highly resilient materials. When combined with hydrated lime, these pozzolans triggered pozzolanic reactions that lead to the formation of calcium silicate hydrates, compounds known for their mechanical strength and chemical durability (Jackson et al., 2014). This Romans' deep understanding of local geo-resources allowed them to optimize the longevity and structural stability of their constructions, providing a valuable model for sustainable material use in modern conservation practices. Despite their durability, natural pozzolanic mortars remain susceptible to deterioration due to environmental exposure and intrinsic factors such as porosity and mineralogical composition. Consequently, effective preservation strategies must be guided by both historical knowledge and scientific analysis to ensure that new restoration materials are compatible with the originals, not only chemically, but also in terms of mechanical and physical properties (Moropolou et al., 2000). This study focuses on developing conservation mortars inspired by Roman techniques, using hydrated lime paste, raw volcanic materials and advanced admixtures to produce formulations that are sustainable and compatible with ancient substrates (Spadavecchia et al., 2024). The research includes the design of various mortar mixes: reference mortars incorporate volcanic aggregates from different Vesuvian eruptions (Avellino, Pompeii, Pollena), simulating the composition of the ancient mortars discovered in the archaeological sites of the area, while experimental mixes include pozzolanic additives such as metakaolin, nano-silica, silica fume, and volcanic ash. Specimens were prepared following ancient methodologies and subjected to extensive laboratory testing. Analytical techniques included X-Ray Diffraction (XRD), Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS), Laser Diffraction, Thermogravimetric Analysis (TGA), and Mercury Intrusion Porosimetry (MIP). Mechanical properties, such as compressive strength, porosity, and water absorption, were evaluated at multiple curing stages (28, 90, 180 days), while durability included resistance to salt crystallization and freeze-thaw cycles after 90 days of curing. The findings of this research contribute to the development of restoration mortars that are both technologically advanced and historically respectful, offering practical solutions for the sustainable conservation of built heritage (Collepardi, 2003).

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Elements distribution (or immobilization) in glass and crystal phases in the treated bottom ash

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Keywords: bottom-ashes, vitrification, immobilization.

Vitrification or solidification of glass-ceramics are common and safe approaches for treating and immobilisation of several inorganic waste; they allow the confinement of environmentally hazardous elements in an amorphous and stable glass (silicate) and /or at crystal nuclei. Here, the chemistry and texture of crystal and glass phases formed from heat treatments of municipal solid waste bottom ashes (BA) are considered. The starting BA composition contains CaO, FeOtot, Al_2O_3, SiO_2, and (Na_2O+K_2O) contents of 17.20, 16.31, 9.31, 46.05 and 6.44 wt.%, respectively (Stabile et al., 2019). This starting material was heated up to an initial T of 900°C at atmospheric P and fO2, reproducing the same conditions used in the municipal solid waste plant. Then, the sample was further heated to the following final conditions 2, 4, 8 and 16 hours at 1000, 1100, 1200 and 1300°C; the experiments were ended by rapidly quenching the run-products in a water bath from high-T to room conditions (estimated quenching rates of 100 C/s).

Back-Scattered Electron (BSE) images and X-ray powder diffraction (XRPD) spectra both show that the main crystal phases are quartz, pyroxene (mainly augite), wollastonite, spinel (Cr-spinel and magnetite). For example, low-T runs at 1000°C (4 h) crystallize mainly diopside and wollastonite; by contrast, the samples at 1200°C (2 and 4 h) resulted enriched in spinel, with Cr substituting for Al in some of the identified crystals, demonstrating the capability to concentrate and stabilize some metal elements (such as Cr or Zn) in these phases.

The textural evolution of the most abundant phases was observed in the low-T runs across the different experimental durations: the texture of wollastonite ranges from elongated, anhedral crystals to needle-shaped ones.

Finally, Attenuated Total Reflection Infrared Spectroscopy (ATR-IR) spectroscopy has been employed on the highest-T run products (final T of 1200 and 1300°C) with a focus mainly on the Si-vibrational modes in comparison with similar compositions of natural analogs glasses. Treated BA ATR-IR spectra mirror those of basalt or trachy-basalt volcanic glasses. The main differences are attributable to higher CaO and lower Al_2O_3 contents than corresponding volcanic analogs. Hence, treated BA could be useful to partially or totally substitute raw-material used to fabricate rock wool or high-temperature basaltic glass fibers for insulation, road base or pavement aggregates).

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Crystal chemistry and physical properties of Orpiment As_2S_3 and relative applications in bidimensional materials science technology: insights from experimental analyses and theoretical simulations

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Keywords: orpiment As_2S_3, 2D minerals, optoelectronics.

Orpiment As_2S_3 (space group P21/n) is a sulphide mineral used since ancient times as yellow and golden pigment, and its name origins from the Latin auripigmentum (Bonazzi & Bindi, 2008). It is common in veins and hot-spring deposits (Gaines et al., 1997) and, aside from its importance in Cultural Heritage, it is a relevant phase in materials science and optoelectronics for its semiconducting properties. From the crystallographic perspective, Orpiment is made of two-dimensional (2D) As_2S_3 layers with strong covalent in-plane As–S bonds held together by long-range (van der Waals) interaction acting along the [010] direction. In addition, a peculiar feature of the Orpiment layers is their buckled structure, very different from other 2D materials like graphene or transition metal dichalcogenides. All these structural and physical-chemical properties make monoclinic As_2S_3 a potential candidate for advanced optical and electronic applications. However, only little information is available in the scientific literature regarding crystalline Orpiment and its 2D structures.

Thus, the purpose of this study is to fill this knowledge gap, presenting detailed experimental and theoretical characterization of the crystallographic, physical (electronic and optical) and vibrational properties of bulk Orpiment and its layered structures. A natural sample provided by the "L. Bombicci" Mineralogy Museum (Bologna) was characterised in detail with X-ray powder diffraction (XRPD), environmental scanning electron microscopy (ESEM) with energy-dispersive microanalysis (EDS) and confocal Raman microspectrometry on both bulk and exfoliated (few-layers) As_2S_3. Atomic-scale data obtained from Density Functional Theory (DFT) with the CRYSTAL code (Dovesi et al., 2018) were then used to interpret the experimental results and to provide further insights into the optoelectronic properties down to the single layer. All-electron Gaussian-type orbitals basis sets and hybrid functionals (B3LYP and HSE06) corrected with the DFT-D3 scheme (Grimme et al., 2015) were used in all the simulations. The results confirmed that bulk Orpiment is a semiconductor with band gap energy Eg = 2.44 eV. We found that the band gap is inversely proportional to the number of layers in the structure (Eg = 3.17 eV in the monolayer). The single- and few-layer structures are, in addition, thermodynamically stable, as observed from the absence of imaginary bands in the phonon dispersion relations, and the energy required by the exfoliation (also known as surface formation energy) is almost constant. This means that producing flakes with different thicknesses is not hindered by energy contributions. This study indicates, most important from the physical and technological point of view, that it is possible to modulate the optical and electronic properties of Orpiment by varying the number of layers in the 2D material, which is of utmost importance for semiconductors and other advanced technological applications.

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New planetary mixer for dry hydration simulation with burnt limes and cementitious by-products

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Keywords: laboratory planetary mixer, CaO-MgO-based hydroxides, green applications.

This study validated various hydration test methods using a custom-built, fully integrated planetary mixer developed for Cimprogetti's Technological Laboratory (Revuelta, 2021). The mixer ensures consistent hydration of diverse burnt limes and cementitious by-products—such as high-calcium quicklime, magnesium-rich dololime, and natural hydraulic lime, as well as fly and bottom ashes—aimed at improving hydration kinetics and enabling the recovery of secondary materials as fillers in construction applications (Sonebi & Diederich, 2016; Martinez et al., 2022). Typically, calcined materials were hydrated with stoichiometric water under optimized conditions to ensure full conversion from oxides to hydroxides (Oates, 1998; Lanas & Alvarez, 2004). In some cases, mixtures were designed with an excess of water and post-hydration drying to convert residual sintered oxides. Hydration recipes were optimized for various green applications, including construction materials (e.g., fillers for plasters, mortars, and concrete), acid neutralization, and flue gas desulfurization (FGD) products (Onestone Consulting, 2024). Both raw and hydrated materials underwent analytical characterization, including Available Lime Index (ALI) by potentiometric titration, slaking reactivity, Quantitative Phase Analysis (QPA-XRPD) via the Rietveld method, Specific Surface Area, Pore Volume, and Pore Size Distribution by nitrogen gas adsorption using the BET and BJH methods. Results confirmed the effectiveness of the new planetary mixer and hydration protocols, particularly for low-reactivity compounds such as dololimes and cementitious by-products. The materials met performance requirements for their intended industrial uses. This work supports the potential reuse of cementitious by-products in construction, opening new opportunities within a circular economy framework. Additionally, it lays the groundwork for developing next-generation green sorbent products for acid neutralization and flue gas desulfurization.

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Investigation of the rheological properties of alkali-activated materials based on volcanic ash and waste glass for 3D printing applications

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Keywords: alkali-activated materials, rheology properties, direct ink writing.

The constantly growing demand for construction materials with a reduced CO_2 footprint has encouraged the use of alkaline-activated materials made from wastes (Provis, 2018). A promising approach to material production, offering both time efficiency and design flexibility, has emerged in Additive Manufacturing (AM) applications, also known as 3D printing (Gibson et al., 2021; Lazorenko & Kasprzhitskii, 2022).

This study investigates the rheological properties of four binary mixtures composed of volcanic ash from Etna (V) and fibre glass (G), an industrial waste provided by Johns Manville (Slovakia). These materials were milled below 40 µm and mixed in different ratios (80:20 and 60:40, of V to G respectively) and activated with 7M or 9M KOH solutions (Zafarana et al., 2024).

The slurries were analysed immediately after mixing, and again after 1 and 2 hours, using a rotational rheometer. All inks exhibited shear-thinning behaviours and rapid structural rebuilding, both essential for shape retention after the printing process. Over time, network formation and structural reinforcement were confirmed by the shift of the crossing points to higher strain levels and an increase in shear stress. Among the four inks tested, the VG1.5(9) formulation (i.e., a 60:40 V-G ratio activated with 9M KOH solution) showed the most promising performance, with a structural rebuilding of 93% at 90 s, and a suitable yield stress to prevent post-extrusion collapse.

3D printing trials of VG1.5(9) highlighted the need to add a rheology modifier to reduce filament spreading. After curing at 60°C for 48 hours, the samples were analysed by using SEM-EDS and for mechanical characterization. SEM-EDS revealed a homogeneous matrix with no signs of delamination surfaces. Compressive strength tests showed values comparable to those of alkaline-activated materials produced by DIW technology.

These results demonstrated the feasibility of up-cycling natural and industrial wastes into sustainable inks for DIW applications. The combination of precursor/activator ratios and the molarity of the alkaline solution enables a balance between extrudability, buildability and mechanical performance. This approach represents a viable way for producing 3D-printed components, contributing to the circular economy and reducing emissions in the construction sector.

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S24.

Integrating the reference geological model in civil engineering projects: approaches and applications

CONVENERS AND CHAIRPERSONS

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Defining the reference geological model in complex geomorphological contexts: the case of a lateral spreading affecting the Adda Riverbanks

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Keywords: landslide, subsurface data, geological model.

This work presents the results of the geological activities carried out in the framework of a project for the construction of a railway crossing of the Adda River (Northern Italy).

The study area, of about 5 km^2, is characterised by tabular summit surfaces constituted by fluvioglacial deposits and incised by the Adda river valley. The river valley slopes are generally steep due to the outcropping of cemented rocks. These rocks belong to a) bedrock sedimentary marine succession of southern Alps, upper Cretaceous-Eocene in age, or b) lower Pleistocene fluvio-glacial cemented conglomerates, locally named as "Ceppo" conglomerates, in sub-horizontal bedding. Conglomerates generally lie on the bedrock formations in angular discordancy. Nevertheless, variable thickness of a clayey formation, locally named "Conche clays" (Pliocene in age), can be stratigraphically present between the bedrock and Ceppo units (Bersezio et al., 2014).

The reference geological model of the area has been defined through the correlation between surface and subsurface data. These allowed to characterize the presence of a deep slope instability developing at the contact between Conche clays and Ceppo conglomerates, affecting both sides of the Adda valley.

In detail, boreholes intercepted the Conche clays and Ceppo conglomerates contact in depth and seismic survey allowed to identify fracturing in conglomerates locally parallel to the terrace cliff. A further constraining element of the model was the outcrops of Conche clays along the riverbanks, mapped during the field survey.

According to our model, the landslide has been triggered by the river incision at the toe of the slope, which exposed the contact between Conche and Ceppo units, leaving conglomerates free to slide downward. Being the contact exposed for hundreds of meters along the valley, the instability currently moves independently of the river erosion. As a consequence, conglomerates disarticulate in blocks that slide, tilt, and topple along the slope, accumulating in the riverbed. Evidence of activity are also present at the top of the valley sides, along the edge of the fluvioglacial terrace, and indicate that the lateral spreading is retrogressively expanding.

The landslide extension is constrained northly by the drastic reduction in thickness of the clays between conglomerate and bedrock, as found in borehole; 2 km on the south, the probable deepening of the Conche-Ceppo contact, testified by the absence of clay outcrops, prevents the landslide to extend. Due to its characteristics, the instability can be classified as a lateral spreading, according to Cruden & Varnes (1996).

In conclusion, this work has contributed to drive the identification of the project solution which resulted less potentially exposed to geological hazards, within the study area.

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The reference geological model in complex infrastructure projects: the examples of the "Marana Tunnel" and the "Vaccarini Viaduct"

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Keywords: seismic retrofit, Marana tunnel, Vaccarini viaduct.

Two complex civil infrastructural projects are presented, in which the definition of the reference geological model has allowed a better optimization of the project in terms of safety, stability of the work and cost-effectiveness.

The Executive Project "S.S 260 Picente Dorsale Amatrice-Montereale-L'Aquila, Lotto IV dallo Svincolo di Marana allo svincolo di Cavallari" involves the seismic retrofit of a road of approximately 6 km, besides the construction of new bridges and viaducts, of a natural tunnel (Marana Tunnel-L = 1130 m) and of an emergency tunnel (1147.3 m). Geological, geomorphological, hydrogeological and seismic surveys and investigations were carried out in order to verify what was proposed in the previous design phases and define the reference geological model of the executive project. Accurate bibliographic research and geological and geomechanical field investigations were carried out. The information obtained was integrated with the results of the geotechnical investigations surveys carried out in the preliminary and definitive design phase (2008 and 2010), by the company Infraengineering srl in the tender phase (2014), and on behalf of Toto Costruzioni Generali spa in the executive design phase (2015-2016).

From the interpretation of the results obtained, new geological, geomorphological and hydrogeological design documents were created, geological profiles and sections were created at the scale of 1:2000 or more detailed.

The investigations conducted in the executive design phase allowed to determine the geometries of some tectonic elements intercepted by the project, making substantial changes to the new reference geological model compared to what was proposed in the previous design phases. In particular, the detailed geological-structural surveys conducted on the south-western side of the Colle Madonna relief allowed to formulate a new interpretative framework of the geological-stratigraphic structure of the significant volume affected by the "Marana" Tunnel. The integrated interpretation of geotechnical and geophysical investigations data permitted a better definition of the geological stratigraphical model of the area, allowing an optimization of the foundation works.

The second case concerns the Executive Project for seismic retrofit of the Vaccarini Viaduct, part of the A24 motorway. An integrated approach was carried out in the interpretation of geological surveys data, geotechnical site and laboratory and geophysical investigations results. This approach led to the definition of the reference geological model in a very detailed scale, necessary for the correct foundations design.

A relevant detail of the engineering geological model of the metro C station "Piazza Venezia" in Rome

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Keywords: 3D geological model, metro station, colluvium.

Among the many surprises that the design and ongoing construction of the line C of Rome underground has provided, this abstract draws attention to a detail of the structure of the subsoil in the area of Piazza Venezia, where one of the stations is being built (Romani et al., 2022). This station will make it possible to bring to light archaeological artefacts and has allowed us to reconstruct the geometry of a slope debris along the buried part of the flank of the Tiber valley.

Piazza Venezia is located on the edge of the recent alluvial plain of the Tiber (Bozzano et al., 2020) and on its southern flank it sees the lateral contact between the recent alluvial deposits and the formations that make up the Capitoline Hill. This contact is now obscured by the thick layer of anthropic fill and by the Vittoriano monument.

The geological substratum of the area is made up, from bottom to top, of the Vatican Marne (upper Pliocene-lower Pleistocene), in which the perimetral diaphragms of the station are embedded, and of the Pleistocene sedimentary and volcanic succession, now partially exposed on the surrounding slopes of the Capitoline Hill.

During the last Glacial Maximum, the valley of the Tiber river was excavated and on the northern flank of the Capitoline Hill, a steep slope about 90 metres in heigh, cut into the geological bedrock, was exposed. The subsequent partial filling of this valley by the Tiber river, from the end of the upper Pleistocene onwards, led to the deposition of recent alluvial deposits. These deposits consist at the base of a layer of gravel overlaid by a main body of fine-grained deposits of low consistency, within which up to a few levels of peat with a lenticular geometry and two lenses of sandy-silt composition have been identified.

The results of the geognostic campaigns carried out for the construction of underground line C have made it possible to 3D reconstruct a geological body lying on the slope of the buried paleo-valley of the Tiber, consisting of silty-sandy deposits with pebbles scattered throughout, including blocks of pyroclastite. It is located between i) the edge of the Tiber paleo-valley, cut into the base of the Capitoline Hill in continuity with the saddle (no longer existing) that separated this relief from the Quirinal Hill and ii) the recent alluvial fill.

The interpretation of the origin of this deposit is that it is a slope deposit, the result of an erosion, transport and accumulation dynamic in the lower-middle part of the original slope, as well as a gravitational dynamic that would have caused blocks of tuff from the top of the hill to fall down to the original valley floor, located tens of metres downhill during the phase of maximum valley incision.

The 3D geometry of this colluvial body has been reconstructed, and on this basis it has been possible to assess its position in relation either to the volume that will be occupied by the Piazza Venezia station or to the tunnels entering into the station.

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Reliability and uncertainty estimation of engineering geological reconstructions along two underground routes in the central Apennines

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Keywords: geological prediction, reliability, aqueduct routes.

The experience on this topic has been achieved through the development of the engineering and geological reconstruction along two major aqueduct routes in central Italy, during the Project of Technical-Economic Feasibility (PFTE) phase. The two routes cross the central Apennines, offering the possibility of dealing with complex settings for the design of construction works.

An “ad hoc” methodology has been developed to assess the reliability of the proposed models and the uncertainties that influence the final design project. By this way, the expert evaluation accounting for these uncertainties has been transferred to the design team, to optimize the investigation insights in the subsequent design phases.

The methodology is inspired by the approach proposed by Bianchi et al. (2012) and considers the contents of a special issue of Engineering Geology journal (Ni et al., 2023).

The proposed geological sections, the corresponding rock quality estimates and, for one of the two routes, the evaluation of the groundwater flow, are accompanied by an assessment of the reliability of the predictions. These predictions are mainly based on the extrapolation of data collected at surface depth to the excavation level. Reliability - geological, geomechanical and hydrogeological – has been expressed in three levels: high, medium and low.

The reliability of the geological reconstruction has been referred to the tunnel elevation and it depends on the availability of onsite surveys and on the difference in elevation between ground level and that of the route. Reliability is optimal at the outcrop level; however, extrapolation of data at depth may be of medium or low reliability in some cases.

The quality of the rock masses is defined on the basis of the results of the surface geomechanical surveys; the geomechanical stations that can be projected onto the routes have been selected on the basis of geological compatibility criteria and a high, medium or low reliability has been assigned on the quality of the station, depending on the absolute difference in elevation between the projection point on the route and that of the route itself, which increases progressively.

For hydrogeology, the reliability of piezometric reconstruction is assessed on the basis of the actual availability of groundwater elevation data (piezometers and springs) and the reliability of the geological reconstruction, which is reflected in the confidence level on the location of the relative contacts between hydrogeological complexes. Linked to the qualitative reliability assessment is an assessment of the likelihood of interaction of the proposed excavation with local and regional aquifers.

Following on from the positive experience here summarized, the scientific objective pursued is a kind of standardization in the assessment of the reliability and uncertainty of geological-technical predictions aimed at the design of construction works.

Acknowledgements: We thank the ACEA group for the opportunity to collaborate.

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The relevance of regional and detailed geological model definition for the excavation of a deep tunnel in hydrogeological sensitive area: a case history from the Brenner Base Tunnel

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Keywords: Hochstegen Zone, hydrogeology, carbonate dissolution.

During the construction of the Brenner Base Tunnel, great emphasis was placed on the development of geological models, both for addressing questions in the approval process and for the planning of tenders related to mechanized and conventional tunneling methods.

In the area of the Hochstegen Zone, a section of the tunnel system approximately 500 meters long, lithologies with potential carbonate dissolution phenomena were predicted based on findings from deep drilling. These features could lead to significant water ingress, thereby affecting ecologically important water resources.

For this reason, strict conditions were imposed during the approval process for this section, including a prohibition on lowering the shallow groundwater level by more than 30 cm.

To carry out tunneling in this section, insights from regional geology were initially required, as the hard rock aquifers are part of a complex nappe structure within the Tauern Window. Geological knowledge from the regional geological model was particularly essential for determining the maximum expected hydraulic pressures, as well as both transient and steady-state water inflows. The model, along with the necessary investigations and analyses, is presented in summary.

During tunneling in this sensitive zone, it became essential to both validate the geological model and adapt its level of detail to meet technical requirements in order to optimize the injection measures being applied. The concept and results of these investigations are presented in this context.

Ultimately, this approach—moving from regional geological modeling to a detailed hydrogeological model—enabled successful tunneling through what was by far the most challenging section from a hydrogeological perspective. The injection methods used led to effective ground improvement, reduced water ingress, and prevented a lowering of the shallow, ecologically significant groundwater levels.

The RGM of the Maddalena Tunnel, a case from the Tunnel Euralpin Lyon Turin

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Keywords: Mont-Cenis tunnel, geological reference model, Ambin Massif.

The 57.5 km Base Tunnel project called “Tunnel du Mont Cenis” is a unique opportunity to learn about the deeper part of the western Alps chain. The twin-tube tunnel project involves crossing the internal part of western Alps from west to east, starting at St. Jean de Maurienne, through the Ultra-Deltafin Zone and cutting the Pennidic Front, then the Subbriançonnais Zone and the Houiller Front, the Briançonnais Houiller Zone, the internal Braincçonnais Zone (Vanoise) the Gipsum Nappe, the Ambin Massif, the Piedmont Zone and the Orsiera Rocciavré oceanic unit at the Susa exit. Over the last 30 years from 1989 to 2007, more than 65 km of deep drilling were carried out, subsequently between 2000 and 2022, 4 large multi-kilometer descendng galleries were excavated. All these investigations have allowed us to gather the elements for a better understanding of the upper crustal part (1000 m) of a “central”sector of the Alpine chain (Egal et al., 2020). At the geological level (in the broadest sense of the term), the exploratory and study phases were carried out in order to acquire sufficient input data to build the most complete geological reference model on a design scale. The goals of these studies and surveys have evolved over time to reduce the risks associated with geology during work. The RGM of the Italian side is the result of a long phase of study begun with detailed geological surveys on the Massif d’Ambin and different campaigns of boreholes following the first proposed track. In 2012, with the approval of the final project, a variant of construction led to the relocation of the site into La Maddalena. In order to define a reliable and precise RGM in a context of high overburden, up to 2000 m, the “Cunicolo della Maddalena” (2013-2017) was excavated with a length of 7 km using Gripper type TBMs (Parisi et al., 2017). The data collected led to the elaboration of the Reference Project in Variant. The last update of the RGM was with the excavation of the niches of La Maddalena, 18 niches for a total lenght of 684 meters excavated with drill & blast in aplitic gneiss of the Ambin Complex and the Clarea Complex micaschist. The comparison of the geological and geomeccanic data collected with the two different methodologies has made it possible to identify some portions with quality rock mass lower than expected and to provide an exhaustive framework for the executive design of the future safety site of Clarea and all the works which will fall in the Massif d’Ambin sector. The construction of geognostic tunnels in high over-burden environments ensures a high reliability of the Geological Reference Model, it has been observed, for example, that rocks with polyphase deformation tend to have a different behaviour depending on the excavation techniques and the orientation of the excavation direction.

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Piscopio I tunnel (Southern Italy): an example of the reference geological model importance in civil engineering projects

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Keywords: reference geological model, Piscopio I Tunnel, excavation phase.

The tunnel Piscopio is a twin-tube tunnel, 750 m long, included in the works of the Maxilotto 2 DG21/04, of the new SS 106 Jonica (Calabria, South Italy). The tunnels have an interaxis of 28 m and an excavation section of about 130 m^2.

The tunnels are in an area close to the Squillace village (south-east side of Catanzaro Trough), characterized by a Miocene and Plio-Pleistocene sedimentary succession which covers, along a non-conformity surface, the crystalline bedrock. The main tectonic lineament is represented by the NE trending Lamezia-Soverato fault zone, morphologically expressed by the Copanello Horst.

During tunnel excavation emerged a lot of data that required to update the reference geological model (RGM). Furthermore, a supplementary geotechnical and geophysical investigation was needed to solve design errors.

The new RGM resulted more complex than the RGM assumed in the design phase. The excavation, initially planned entirely in gypsum, has instead crossed: (i) gypsarenites (Miocene), (ii) a chaotic facies made by a clayey matrix included angular fragments and block (also decametric) of gypsarenites, (iii) an alternance of silty clay and sandy gravel with Plio-Pleistocene age.

The tectonic setting, derived from outcrop data and geomechanical surveys along the excavation tunnel faces, consists of a main NW-SE oriented fault (N210/80), with predominantly extensional kinematics, and at least three secondary faults systems (N105/50, N260/45, N10/20).

During the building phase, a complex landslide along the left hydrographic side of the Alessi River interfered with the tunnel excavation. The slope movement was triggered when the tunnel excavation (from the opposite slope) crossed the watershed simultaneously with a significant pluviometric event (November 2011). We improved geomorphological assessment by means of multitemporal photointerpretation, in-situ topographic and inclinometer monitoring, and field surveys. Collected data allowed to identify different movements controlled by the lithostratigraphic setting and tectonic lineaments. We also identified the landslide predisposing factors represented by: (i) the high local relief, due to the ancient geomorphological setting; (ii) the poor physico-mechanical characteristics of gypsum rocks, due to dissolution favored by the presence of water table; (iii) the rainfall peak recorded during November 2011.

The revised RGM allowed us to evaluate the most appropriate systems for landslide stabilization (land taking back and deep drainage systems) and for tunnel consolidation and excavation (contour consolidation with unreinforced piles realized from the surface). The excavation was completed without any problems and without exceeding the monitoring thresholds of attention.

Three-dimensional geological modelling of the Cassino Basin (central Italy) for seismic risk mitigation in civil and environmental engineering applications

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Keywords: 3D geological modelling, seismic risk mitigation, Cassino intermontane basin.

Integrating detailed geological models into civil and environmental engineering projects is fundamental for an informed infrastructure design and an accurate seismic risk assessment, particularly in complex tectonic and hydrogeological settings. This work illustrates the methodological approaches and practical applications for developing a 3D geological model of the Cassino Plain, an intermontane basin of central Italy characterised by a significant seismic hazard and complex hydrogeological conditions. The area is affected by major infrastructures, including the initial part of the Western Campania Aqueduct. The study involves comprehensive geophysical, geological, hydrogeological and geotechnical analyses, combining borehole data, seismic ambient noise measurements, and advanced geostatistical techniques to delineate the bedrock's morphology and reconstruct a 3D geological reference model. The Cassino Basin, formed during Pliocene-Pleistocene tectonic activity, features a complex horst-and-graben arrangement with varying thicknesses of Quaternary alluvial sediments resting on carbonate and arenaceous bedrock (Saroli et al., 2020). Past seismic events highlight the need for precise identification of the seismic bedrock to evaluate local seismic amplification phenomena effectively. This study integrated 130 boreholes extending to depths down to 350 m b.g.l. and more than 260 seismic ambient noise measurements to create a detailed 3D geometrical model of the bedrock. Seismic ambient noise data, analysed via Horizontal-to-Vertical Spectral Ratio (HVSR), revealed pronounced impedance contrasts and provided precise mapping of resonance frequencies, which correlated very well with the bedrock depth available from borehole data. Advanced geostatistical interpolation was utilised to transform scattered geophysical measurements into a coherent, spatially continuous map. This enabled the identification of the seismic bedrock surface and facilitated the estimation of sediment thickness through empirically derived relationships between resonant frequency and soil thickness (D'Amico et al., 2008; Van Noten et al., 2022). Virtual boreholes have been generated to augment physical subsurface investigations, which, together with real boreholes, significantly enhanced the resolution and reliability of the 3D geological reference model of the basin. Available boreholes were further exploited to classify the Quaternary filling below the city centre, defining at least four lithological layers, characterised by specific geotechnical properties, and two different aquifers: a shallow multi-level hydrostratigraphic aquifer and a deep pressurised aquifer. The integrated model supports civil engineering by enhancing site-specific seismic hazard assessment, soil-structure interaction analysis, and infrastructure resilience. It proves the value of multidisciplinary geological modelling in reducing uncertainties and seismic risk in complex settings.

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3D kinematic analysis and block volume estimation of rock slope using point clouds and innovative digital methods

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Keywords: rock slope stability, digital photogrammetry, volume estimation.

Recent advancements in photogrammetry and Structure from Motion (SfM) algorithms have significantly improved the fracture analysis and geomechanical characterization of rock masses. Enhanced sensors and Remotely Piloted Aircraft Systems (RPAS) have made digital photogrammetry more efficient, safe, and cost-effective for rock slope assessments. The growth in computational power and specialized software has improved 3D data extraction, especially for discontinuity network characterization. However, the lack of automatic workflows still limits comprehensive analysis of large 3D datasets. Traditional methods like the Markland Test do not fully utilize the detailed geometric and spatial data now available. For this reason, we present an innovative workflow designed to enhance both robustness and effectiveness in identifying, analyzing, and prioritizing criticalities within fractured rock slopes. Thanks to the collaboration with Italferr s.p.a, the proposed methodology has been applied to the Molassana quarry, within the new Genova metropolitan line project, *SkyMetro*. The proposed workflow integrates multiple complementary steps:

Field-based structural characterization of the polydeformed rock slope

Manual extraction of discontinuity data from high-resolution Digital Outcrop Model (DOM) (Perozzo et al., 2024).

Kinematic analysis using the automated Rock slope Kinematic Analysis (ROKA; Menegoni et al., 2021) algorithm, offering an advanced version of the classical Markland Test.

Quantitative evaluation of fracture intensity through the Discontinuity Intensity Calculator and Estimator (DICE; Menegoni et al., 2022) algorithm, enabling detailed assessment of fracture density.

Integration of micro-fracturing features observed directly from drone-captured images to refine the microfracture network characterization.

Calculation of the volumes of potential rock blocks derived from a spacing analysis.

Validation of the results through a 3D model-based interpretation (G3 https://doi.org/10.5194/esurf-10-1211-2022 Point; Steer et al., 2022) of the rock block deposits at the slope toe.

This integrated approach highlights the advantages of merging traditional geological interpretation with advanced digital technologies, offering a more comprehensive and data-driven method for assessing rock slope stability, especially in the planning of large-scale infrastructure projects.

Menegoni N. et al. (2021) - An open-source algorithm for 3D rock slope kinematic analysis (ROKA). Applied Sciences, 11(4), 1698, https://doi.org/10.3390/app11041698.

Menegoni N. et al. (2022) - DICE: An open-source MATLAB application for quantification and parametrization of digital outcrop model-based fracture datasets. Journal of Rock Mechanics and Geotechnical Engineering, 15(5), 1090-1110, https://doi.org/10.1016/j.jrmge.2022.09.011.

Steer P. et al. (2022) - Size, shape and orientation matter: fast and semi-automatic measurement of grain geometries from 3D point clouds. Earth Surface Dynamics, 10(6), 1211-1232, https://doi.org/10.5194/esurf-10-1211-2022.

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The strategical function of the geological studies in the Technical-Economic Feasibility Project of the new Italian Contract Code

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Keywords: geological studies, Italian Contract Code, PFTE.

The experience of the authors in the examination of the Technical and Economic Feasibility Projects (hereinafter PFTE) of the major works of the PNRR as Members expert of Geology and Engineering Geology in the Italian High Bord for Public Works has allowed them to develop a series of reflections on the role of geology in the context of design processes.

The geological knowledge of the territory and its dynamics has a decisive strategic role in relation to the choices of a design and planning nature, in terms of contingent choices in relation to the territorial context in which they are inserted. Thus leading, among other things, to the expansion of the concept of durability of the works also in relation to the interaction with the territory. This is a particularly relevant in a geologically young territory such as Italy, physiologically subject to an intense active tectonics and geomorphological dynamics that often manifests itself with catastrophic events that can be classified as Natural Risks (Natural Hazard).

The new Italian Contract code has brought the design levels to two: PFTE and Executive Project, but there are other strategic design moments upstream that have to consider the relevance of geological aspects. The "Feasibility Document of Design Alternatives" (DOCFAP) which cannot ignore a geological, geomorphological and hydrogeological analysis to evaluate the feasibility of the options considering geological critical aspects that could influence the choices. Then there is the "Design Direction Document" (DIP) which highlights the technical requirements that the intervention must satisfy taking into account the criticalities of the territory. The PFTE defined as "Knowledge Project" is a strategic moment aimed at giving certainty to the design forecasts relating to the chosen solution. It includes all the knowledge activities and essential design choices. This is the phase all geological aspects must be defined in detail, without delegating to subsequent phases geological evaluations that could influence the design choices. It is fundament to give certainty to the design forecasts and to construction times in order to guarantee the stability, safety and durability of the works over time.

It is to avoid a Justifying Geology, a mere formal fulfillment in support of design choices already made. The typological and constructive choices should be made taking into account the interaction of the works with the territory. also in relation to the problems of durability and maintenance of the works themselves.

Those involved in the design and/or management of the works must have adequate ability to evaluate the critical issues connected to the geological characteristics of the territory to guide the decision-making processes and therefore be an integral part of the design.

The importance of a Reference Geological Model in underground tunnel construction: the Abatemarco water pipeline case study (Cosenza, Southern Italy)

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Keywords: Geological Model, water pipeline, Abatemarco.

Evaluating the Reference Geological Model (RGM) is crucial during the design and construction of underground tunnels. It enables accurate assessment of technical and financial risks, as well as environmental hazards that may arise from potential interactions between underground works and water resources, such as water tables, lakes, or springs. In contrast, inaccurate geological forecasts may compromise the tunnelling project, even if it is impossible to eliminate all uncertainties affecting geological models. This paper focuses on the geological model drafted for the Abatemarco underground tunnel project. The project consisted of excavating a 6.270 km-long tunnel, through the Coastal Range (Calabria, Southern Italy), to capture two springs (Favata and Nascejume springs) capable of furnishing a water flow rate of 200 l/s to Cosenza settlement and 25 neighbouring municipalities located at a distance of 70 km from the tunnel. The latter is located at an altitude of 622 m on the Coastal Range east flank and 657 m on the west flank, crossing the central portion of the Mula massif with a N140° direction. The excavation works began in November 1979 and were completed in December 1982. The project planned excavation works without water inflow, as it involved mainly impermeable phyllite rocks and a small portion of carbonate rocks, both part of the sedimentary succession of the S. Donato Unit (Ietto & Barillaro, 1993). The S. Donato Unit, Triassic in age, consists of three main intervals in stratigraphic contact (Barca et al., 2010): 1) Basal Terrigenous Complex, made up of siliciclastic sediments (phyllites) with limestone intercalation; 2) Intermediate Carbonate Complex, consisting of a shelf margin limestone sequence; 3) Upper Marly Dolomitic Complex, characterised by a dolomitic succession. Contrary to the original geological model, abundant water flows were recorded at 1500 m of excavation. The water flow reached up to 874 l/s with a pressure of 12 atm, ultimately stabilising at a flow rate of approximately 500 l/s. Consequently, the tunnel project was modified from a water transport tunnel to a drainage tunnel. A latest detailed geological field survey, coupled with the analysis of data collected during the tunnel excavation phases, led to the development of a new geological model. The model reveals the existence of a monocline fold, not recognised within the original geological model. The fold structure has an axis in the N120° direction, dips to the NE, and consists of carbonate rocks and phyllites that form the core of the fold structure. Consequently, the abundant water flows in the carbonate rocks, recorded during the excavation works, were due to water circulation within the reverse flank of the fold structure, forming a confined aquifer with phyllite rocks at the top. This case study emphasises the importance of an accurate Geological Model in engineering projects to identify and manage excavation risks while reducing costs.

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The central role of the geological model in seismic assessment of large dams: from basin geohazard analysis to foundation insights

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Keywords: geological modeling, geohazards, dams.

The reconstruction of a robust geological model, developed through an integrated approach that combines geological, geomorphological, geotechnical and seismotectonic analyses, is essential in the context of the seismic assessments of large dams.

In the context of this kind of major engineering works, the geological model plays a crucial role at different scales, from regional, to foundation, passing from basin-size.

The current Italian technical code for dams (NTD 2014) highlights the importance of seismotectonic investigations, prescribing specific seismic hazard analyses for each structure located in high seismic hazard zones. These studies assume an evident key role also for defining scenarios of epicentral seismic forcing, in case of dams placed near seismogenic sources.

A crucial aspect in the recognition of dam-referred geohazards concerns also the identification and characterisation of active and capable faults below the foundation area or in the surrounding zones, whose possible movement can lead to dam failures and uncontrolled loss of the storage water.

Furthermore, the stability of the reservoir slopes must be evaluated, also considering dynamic scenarios induced by potential earthquakes, in order to identify the risk of outlet obstruction and the generation of impulsive waves capable of overtopping the dam crest.

Finally, the geological model serves as a reference for a correct geotechnical reconstruction and parametrisation of the foundation area, that is crucial for the seismic assessment of dams.

This integrated approach allows for increasing the reliability of numerical models and supports informed decision-making processes regarding the seismic safety and the operational management of large dam infrastructures.

Evaluation of errors in construction and evolution of extreme rainfall events – Geomorphological study and reduction of hydraulic vulnerability of SP 70 at Km 12+260

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Keywords: landscape evolution, geohazard.

The Province of Southern Sardinia has planned various safety interventions for multiple sections of road under its jurisdiction, subject to flooding phenomena and in particular the critical issues present at hydraulic intersections. Among these, particular attention has been paid to the persistent problems at Km 12+260 of provincial road no. 70, in the locality of "Is Cattas" in the Municipality of Santadi, at a hydraulic crossing consisting of a "Finsider" pipeline. The problems concern the narrowness of the crossing in relation to the exceptional rainfall events "Mediterranean cyclones" that now periodically hit Sardinia.

In fact, the original sizing of the work is not able to withstand the greater hydraulic flows that occur, with a particular peak of criticality that occurred on 11/14/2021. This event led to the almost complete erosion of the sides of the finsider pipe, causing the collapse of the road for a stretch of over 20 meters. From a careful survey carried out by geologists from the Province's Road Service, it was possible to ascertain that the work was built by actually diverting the original natural flow, with a rotation of almost 90 degrees of the river bed at the road, leading to a corresponding increase in the hydraulic head, especially in the event of exceptional rainfall events.

The hydraulic crossing has been restored pending the collection of the funds needed to adapt the work of art or its possible replacement following a careful hydrogeological and especially geomorphological study, in order to model the best balance profile of the watercourse capable of supporting the new hydraulic regimes of the section. The resources set aside and programmed by the Province for 2025 and 2026 will be sufficient for the planning, design and execution of the new work, capable of reducing the persistent danger in correspondence with the town of Is Cattas, with the provision of implementing a monitoring system regarding the water levels of outflow, as well as the liquid and solid flows that will cross the new work of art.

Reliability of Reference Geological Model: preliminary study to implement verification and validation techniques

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Keywords: Reference Geological Model, reliability, tunnels.

Infrastructure development is essential for economic growth, social progress and improved living conditions. Among the key elements, underground structures, especially tunnels, stand out as essential solutions to connect territories, support transportation systems and overcome geomorphological and geographical barriers. From primitive tunnels of ancient civilizations to modern mechanized techniques, tunnel construction reflects human innovation and adaptability through civil engineering.

The quality of tunnel design and construction is directly linked to the level of understanding of the geological, geotechnical, geomechanical and hydrogeological conditions of the project area. These aspects are captured in Geological Reference Models, which, despite their importance, always include a degree of uncertainty due to the complexity of natural systems. These models provide simplified representations of surface and subsurface realities, supporting the design of infrastructure such as roads, tunnels, bridges, foundations, dams and offshore platforms.

This study focuses on the evaluation and verification of the reliability of geological reference models in the design and construction oh railway tunnels. Two case studies were selected, each characterized by distinct geological contexts. The first tunnel, about 1.7 km long, crosses terraced alluvial deposits with three lithofacies: polygenic and heterometric gravels, silty sands and clayey silts. The second, about 2.2 km long, crosses the Varicolor Clays, including silty and sandy clays, stratified or massive limestones and alternations of clay and limestone. Both tunnels were divided according to geological complexity: 100-meter sections in simple areas and 50-meter sections in more complex areas. Two indices were calculated to evaluate the reliability of the models: the R index and the Geological Model Rating (GMR). These depend on three main groups of parameters: investigation parameters, characteristics of the geological sy stem and interpreter competence.

Model verification was conducted by comparing the initial geological models with data collected during excavations, including over 200 surveyed excavation face sheets. Preliminary results show that in the first case study, where the geological complexity is relatively low, the model corresponds well to the real conditions. However, in the second case, where the geological structures are more complex, significant discrepancies between the model predictions and the reality on the ground were observed.

Integrated monitoring strategies for enhancing resilience in railway network development

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Keywords: landslide monitoring, remote sensing, rail network development.

In recent years, the increasing impact of landslide events on critical infrastructure has underscored the urgent need for advanced monitoring frameworks to support risk mitigation across all phases of railway network development, from feasibility studies to operational stages. This research addresses this challenge by proposing an integrated methodology that synergizes data from satellite-based Interferometric Synthetic Aperture Radar (InSAR) and conventional monitoring systems such as inclinometric measurements. The approach aims to enhance the precision of slope instability assessments in structurally complex geological settings, particularly in areas characterized by heterogeneous lithologies with clay-rich horizons, where intermittent slope deformations are often prevalent.

By correlating time-series displacement data from remote sensing with ground-based inclinometric measurements, the study validates the complementary strengths of these methodologies. The integration enables (1) robust validation of remote sensing outputs in localized geological contexts, (2) high-resolution spatiotemporal mapping of deformation patterns, and (3) identification of critical zones requiring prioritized intervention along planned railway alignments. Initial applications in feasibility studies for new rail routes crossing regions affected by slope instability demonstrate a strong correlation between satellite-derived and inclinometric displacement trends. This highlights the method's capability to resolve coupled surface and subsurface kinematic processes.

The framework supports proactive hazard management by integrating multiparametric datasets in unstable slopes, providing a scalable solution for optimizing railway paths and supporting mitigation measures during infrastructure design. Future developments focus on automating data harmonization processes to enable real-time integrated visualization of multi-sensor data, thereby improving decision-making efficiency. This research emphasizes the critical role of interdisciplinary monitoring strategies in building resilient transportation networks, providing transferable insights for infrastructure projects in geodynamically active regions worldwide.

Assessment of the lithological and depositional characteristics of the Flysch Rosso within the context of the Napoli–Bari railway line

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Keywords: Flysch Rosso, complex formations, spatial variability.

This contribution highlights the importance of accurately studying the lithological and depositional characteristics within the context of a complex formation to support geotechnical and structural tunnel design. This study focuses on a stretch of the Napoli–Bari railway line (under construction) located between Melito and Grottaminarda, in the Southern Apennines. In this stretch, two tunnels of about 4 km and 2 km in length cross a significant volume of the Flysch Rosso. The Flysch Rosso is a formation that belongs to the Frigento unit, which constitutes a part of the innermost sector of the Lagonegrese-Molisano Basin.

Despite reference scientific literature for this area (CARG map n. 433, Ariano Irpino) shows the occurrence of two spatially distinct lithofacies for the Flysch Rosso formation, FYR (mainly marls and clays) and FYR2 (mainly limestones), detailed geological surveys and borehole investigations revealed a more complex lithological and structural formation.

The results allowed for the definition of a more detailed geological model, addressing both depositional environment reconstruction and spatial mapping of different sub-units. The detailed analysis of the lithofacies sampled from numerous boreholes within the Flysch Rosso allowed the recognition of a member referable to a chaotic formation in geological terms, or a “bimrock” (block-in-matrix rock; Medley, 1994) in geomechanical terms. The introduction of this sub-unit into the geological profiles of the line is significant from the perspective of adequate engineering characterization functional to the geotechnical parameterization of the mass. Within the chaotic member, a further subdivision of lithofacies was carried out based on the different relationships between blocks/clasts and matrix in the various sectors of the route. Therefore, FYRca (blocks/clasts < 10%, matrix > 90%), FYRcb (blocks/clasts ~ 20%, matrix ~ 80%), and FYRcc (blocks/clasts ~ 40%, matrix ~ 60%) were recognized. This classification is quite similar to the one later proposed by Napoli et al. (2022) for geotechnically complex formations with block-in-matrix fabrics. These insights provided significant support for mechanical excavation design.

This contribution emphasizes the importance of reconstructing both the original depositional environment and the spatial variability of the lithofacies in civil engineering projects involving complex geological formations. This approach ensures accurate geological understanding and provides critical engineering characterization for the geotechnical parameterization of the rock mass.

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Reliability and unforeseen in geological models for civil works: the responsibilities carousel

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Keywords: reference geological model (RGM), geological unforeseen, reliability.

In civil works design and construction, reliability and unforeseen of reference geological models (RGM) are far more than a simple technical matter; they have relevant financial and legal meanings. Even further, RGM cannot be considered as a responsibility of just geologists, because many external actors play a role in this field.

Between reliability and unforeseen an inverse correlation exists: the higher the reliability, the lower the probability that an unforeseen occurs. Depending on reasons determining a higher or lower reliability, two types of unforeseen exist, which is relevant form a legal point of view: 1) unforeseen depending on a lack of investigations or interpretation (epistemic); 2) unforeseen depending on an unavoidable lack of knowledge due to the system complexity (aleatoric). The first implies someone's responsibility for unforeseen consequences, while the second does not.

An analysis of the main elements influencing a RGM helps addressing the problem; these can be identified as follows: a) geological context complexity, b) interpretation quality, c) investigations quality (mapping, drillholes, geophysics). The aspect *a* is an imposed condition on which project promoters have no influence; it always implies a degree of aleatoric uncertainty. On the contrary, aspects *b* and *c* have an epistemic character, and strongly depend on the project promoters' decisions. Among these there also are geologists, but it is worth noting that other subjects contribute. For example, time available to develop the project, a key factor influencing quality, is decided by contracting entities. Similarly, the number and quality of site investigations is influenced by the budget defined by contracting entities or contractors. Some data derived from investigations, as for example geophysical investigations, require a specialist interpretation, that often appears as a black box to other subjects and whose reliability is unknown.

Previous remarks should have relevant impacts on responsibilities in the frame of the procurement legislation. Firstly, owing to the cited limitations imposed by design times, budget and interpretations commingling, it is impossible to assume that the last design level before construction (Progetto Esecutivo in Italian law) leave no open questions as underlying in some contractual structure (e.g. Appalto Integrato). A shared method for estimating RGM reliability should be pursued by clients and contractors. This would allow contracting entities to define which reliability degree is reasonably acceptable as a function of required design and construction times. Both parties should be aware of implications that their choices have on RGM reliability and assume their responsibilities. To minimize litigations, contracts should be managed as a function of a shared RGM reliability. Finally, geologists who created the RGM cannot be charged of responsibility for unforeseen consequences irrespective of other actors' decisions.

The Einstein Telescope in Sardinia: geological insights within the framework of a pre-feasibility study

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Keywords: Einstein Telescope, RGM.

The Einstein Telescope (ET) is one of the leading European research projects with global scientific impact. Italy is a candidate to host it in Sardinia, around the disused Sos Enattos mine near Nuoro. This large underground facility will house a third-generation gravitational wave detector, capable of observing a volume of the universe about one thousand times larger than current second-generation instruments, such as the LIGO interferometers in the United States and Virgo in Italy. The ET is named for its ability to "observe" gravitational waves arriving on Earth from deep space. The Italian site is competing with another candidate site in the Netherlands, on the border between the Netherlands, Belgium, and Germany. The ET project explores two primary configurations for its underground observatory: the T-shaped and the L-shaped designs, featuring 10 km-long and 15 km-long arms, respectively. Both configurations are situated 250 up to 400 meters underground and, at their vertices, the construction of a complex series of caverns (up to 35 meters high) is planned, which will house the technological components of the observatory.

One of the various activities currently underway as part of the pre-feasibility study for the candidate site in Sardinia involves the reconstruction of the geological model that serves as a reference for the design of the underground works. From a geological point of view, the ET site in Sardinia is located in the Variscan Belt, mainly in a sector of the so-called "Medium-Grade Metamorphic Complex" (MGMC) of the Internal Nappe Zone, consisting of Cambrian to Ordovician (Carmignani et al., 1995) metasedimentary and Ordovician orthogneiss reaching amphibolite-facies conditions. These rocks are intruded by late- to post-Variscan granitoids that largely outcrop in the area.

The first phase involved planning the investigations, with particular focus on the vertex locations of the T and L configurations, as these are the most sensitive components of the underground observatory, requiring special attention to potential geomechanical and hydrogeological issues. The investigations included 11 boreholes with a total length of more than 4'000 m (2'700 meters were carried out with continuous coring), borehole logging, dilatometric and hydraulic tests, gas Radon detection, and about 5'000 m of cumulative length of seismic reflection profiles. The second phase involved the integration of extensive geological surveys, structural and geomechanical data, and investigation results with the aim of defining the Reference Geological Model and assessing more precisely the geological and hydrogeological risks related to the realization of the underground observatory.

Although the study and the investigations are currently ongoing, the preliminary reference geological model suggests suitable geomechanical and hydrogeological conditions at the level of the underground observatory.

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Reference Geological Model of the reconstruction viaduct S. Giorgio in Genoa (IT) (ex Morandi bridge)

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Keywords: Reference Geological Model of ex-Morandi bridge, reconstruction viaduct, Genoa.

The reconstruction project of the S. Giorgio Viaduct in Genoa (IT) is set in an extremely complex geological-structural sector of the Ligurian Alps, characterized by the presence of various bedrock formations, which can be traced back to tectonic-structural units resulting from both Alpine and subsequent Apennine orogenesis.

This specific sector is composed of the superposition of oceanic crust and mantle units (Figogna, Palmaro-Caffarella, Cravasco-Voltaggio e Voltri), re-equilibrated at different depths, with thermal gradients ranging from low to very low, and sedimentary, non-metamorphic or low metamorphic, flysch units (Antola, Ronco, Montanesi and Mignanego).

The quaternary deposits unconformably overlying bedrock formations and are attributable to alluvial and marine deposits, eluvio-colluvial deposits and significant anthropogenic fills, especially on the left hydraulic side of the valley.

The Polcevera Valley, where the viaduct is located, is dominated by continuous successions of argillaceous schists, argillites, and flyschoid units, which create rather soft morphologies despite being characterized by steep slopes. The area is characterized by a limited number of landslide phenomena, mostly dormant, which mainly affect the eluvio-colluvial deposits and are predominantly translational and flow types.

In general, underground water circulation occurs in the more permeable alluvial deposits, where an important phreatic aquifer is found, characterized by a rather shallow piezometric surface that follows the morphological trend of the valley floor.

To support the various design phases, were conducted numerous detailed investigations, consisting of geognostic borehole tests, geophysical surveys and laboratory tests on samples taken from boreholes.

In addition, reference was also made to the surveys form archives related to various past projects on the area and from the geognostic database of the Liguria Region.

The set of all investigations led to the definition of a detailed geological map of the area and the reconstruction of an accurate Reference Geological Model of the sector under examination, graphically summarized in a geological-technical profile along the viaduct axis.

The results obtained from seismic surveys and boreholes, together with surface geological surveys, allowed the reconstruction of the three-dimensional trend of the bedrock's roof. The surface of the bedrock's roof was also reconstructed based on the analysis of resonance frequencies obtained from the numerous HVSR tests performed, calibrated through direct survey's data and then spatially interpolated.

To provide an interactive 3D model, the surfaces related to the bedrock's roof surface, the ground level, the digital terrain model (DTM) and geological sections along and across the viaduct were imported into a structural Bim Authoring tool. Additionally. Thus made it possible to insert and visualize in three-dimensional space the infrastructure in its reference geological reference context.

Geological reference model at the Brenner Base Tunnel - development, application and verification

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Keywords: Brenner Base Tunnel, geological reference model.

The Brenner Base Tunnel (BBT) is a railway connection running beneath the Italian and Austrian Alps for 64 km under high overburdens. The BBT consists of two Main Tunnels, each with a diameter of about 10 m, spaced 40-70 m apart and linked every 333 m by connecting side tunnels. A peculiar feature of the BBT is the Exploratory Tunnel running between the two tubes and about 12 m below them with a diameter of 6-8 m.

The geological and geotechnical model was developed in 3 phases at great expense.

In phase I, in addition to seismic and gravimetric explorations and the start of a continuous hydrogeological monitoring, 9 exploratory boreholes were drilled and approximately 540 km² of area were mapped according to geological and structural geological criteria. The aim of this first phase was to revise the feasibility study from 1987, to pre-select a route and to provide an estimation of construction costs, construction time and risks.

Based on this data, the two countries Austria and Italy decided to carry out the project. Phase II was launched with the aim of optimising the route, obtaining all permits on both national territories (preliminary design) and providing all data for the technical project preparation. The programme included supplementary and in-depth mapping at various scales and at portal areas, a large drilling programme with over 200 exploratory boreholes with over 30,000 metres of core samples, investigations in the boreholes, laboratory tests on the rock samples, geophysical investigations around valley crossings and portal areas and critical slopes. The results were numerous geological surface maps over the entire route area, geological and geotechnical longitudinal and transverse profiles, a geological-structural geological map at tunnel level and ground models at route level.

As a cross-border project, the Austrian guidelines were used in addition to the Italian standards for the geotechnical route assessment, causing interesting and important synergy effects. First based on the geological model, relevant parameters of the different lithological units were defined and rock masses with similar characteristics were grouped into ground types. The second step involved the evaluation of the rock behaviours, considering each rock types and the influencing factors discontinuity orientation to the tunnel axis, ground water conditions, in situ stress. These data were represented in the geotechnical longitudinal section. The tunnelling classes were determined based on the rock behaviour types.

In phase III, the construction of the continuous Exploratory Tunnel started in 2007. This is a peculiar feature of the BBT compared to other large transalpine railway tunnels. In addition to geological exploration, its main functions are logistics and tunnel water drainage in the construction phase but also tunnel maintenance during the operating phase. Fault zones and geologically critical zones were explored in advance, which allowed to optimize the design and excavation of the main tubes with less advance exploration measures.

As most of the tunnels on the Italian side have already been excavated, a comparison of the geological reference model with the as-built situation is carried out. It has been shown that the large-scale mapping and drilling campaigns in the design phase and continuous overlapping advance drilling performed in the construction phase were the best investments to avoid very cost-intensive and time-consuming delays and shutdowns of the advances.

Landslide and infrastructure interaction: the Ligea landslide system case study

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Keywords: landslide system, geomorphological model, hillslope evolution model.

The Ligea landslide system is located west of the city of Salerno, along the hillsides of the coast, covering an area of approximately 0.4 km^2. This location is considered critical because several structures and infrastructures have been built in recent decades along the south-facing hillside where the movements take place. The unstable area interferes with a strategic infrastructural corridor consisting of the 'A3 Naples-Salerno' highway, the 'Naples-Battipaglia' railway, the 'SS18 Tirrena Inferiore' state road, the commercial port of Salerno and related infrastructure, as well as civil and industrial buildings. The phenomenon had previously been reported as DSGSD (UoM Desta Sele, 2011), but the latest geological and geomorphological survey activities and in situ tests have provided much more detail on the movements. The main geological model of the hillslope consists of mesozoic limestones and marls with secondary dolostones in the higher portion; such materials are often mechanically degraded by tectonic lineaments (Iannace et al., 2021). From a geomorphological point of view, however, the surface features describe a convoluted gravitational history. The earliest and 'basal' movement can be described as a rotational landslide (*sensu* Hungr et al., 2014) that can be clearly limited in the area of detachment, but not at its face due to the intense anthropogenic remodelling of the hill foot and its probable submarine development. The already degraded mass of this object has further disaggregated into different portions that have moved and evolved at different rates in the form of different types of rock/debris slides. Today, the main processes are rockfalls occurring on cliffs produced by the main escarpment of the oldest movement and other escarpments related to subsequent movements, and debris flows occurring along streams and channels developed on and around the main mass. Recognition of this spatial and temporal arrangement of movements made it possible to classify the set of processes in the definition of a landslide system (*sensu* Valiante et al., 2021). The description of the landslide system provides a better understanding of the functional interactions between past events and ongoing movements. This makes it possible to formulate future scenarios that can be seamlessly integrated into geological and geomorphological slope models, leading to a more complete understanding of slope evolution and improving hazard assessment.

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S25.

Advanced waste valorization: transforming waste to geo-resources

CONVENERS AND CHAIRPERSONS

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Pickling wastes: fluoride recovery with precipitation of fluorapatites

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Keywords: industrial recovery, wastewaters, fluorides.

The industrial heat treatment of stainless steel produces a surface reaction between metals and atmospheric oxygen. For this reason, a surface layer of iron, chromium and molybdenum oxides forms on the material, which must be removed to ensure solid properties of the steel's surface. This removal, for certain materials, is carried out through a chemical process called pickling, which involves the use of concentrated acids (i.e. sulfuric and hydrofluoric acid). The result of this entire process is an extremely aggressive pickling liquor, rich in heavy metals and fluorides dissolved into the solution as main contaminants. The pickling liquor is then treated and finally the solid component (pickling sludge) and the liquid component (wastewaters) are disposed of.

In recent decades, the focus on these contaminants has significantly increased due to the risks they pose to public health. Here, we propose to study the recovery of pickling liquor through the application of mineralogy and crystal growth principles. The essential conditions for the safe storage of pollutants are their complete immobilization: this will be obtained by exploiting the intrinsic properties of some minerals such as stability according to temperature, chemistry of the surrounding environment, and low solubility. Regarding fluorides, octacalcium phosphate - OCP ($Ca_8(HPO_4)_2(PO_4)_4$) has proven particularly effective in removing high concentrations of this contaminant in water by transforming into fluorapatite (Idini et al., 2019). This mineral has already been successfully used to abate fluoride in groundwater intended for human consumption (Idini et al., 2020).

However, the direct fluoride removal in complex solutions resulting from industrial treatments has never been explored. Therefore, thanks to the valuable collaboration between the University of Turin and Cogne Acciai Speciali SpA, we had the opportunity to test the fluoride capture reaction using octacalcium phosphate in a real industrial environment. Our preliminary results demonstrate the effectiveness of OCP removing fluoride from industrial solutions, highlighting its potential for industrial large-scale applications. OCP promotes the precipitation of fluoroapatite, with complete removal of the fluoride from the solution. This opens doors to the use of OCP as a viable reagent for treating wastewater, enabling fluoride concentrations to be reduced well below the environmental limits set by European regulations.

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Characterization and valorization potential of RDF bottom ash from the incineration of anaerobic digestate of municipal solid waste

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Keywords: refuse-derived fuel, waste incineration, bottom ash.

In 2023, 119 municipal solid waste (MSW) incinerators operated across France, treating approximately 15 million tonnes of waste, with 116 of them functioning as waste-to-energy (WtE) plants (ADEME, 2023). A sub-sector of incineration is growing to enhance energy recovery: the production of Refuse-Derived Fuels (RDF) (Santos et al., 2023). These fuels are typically composed of non-hazardous solid waste that cannot be valorized through material recovery or conventional sorting channels (Chang et al., 1998). Their preparation involves the removal of non-combustible or low-energy-value materials and moisture reduction to optimize their heating value. RDF are usually combusted in dedicated boilers either on-site or by nearby industries (e.g., cement kilns), aligning with circular economy principles through localized energy production (Shehata, et al., 2022). In 2024, France had launched 19 RDF valorization projects, with a total potential of 1.4 million tonnes of RDF and 700 MW of capacity (ADEME, 2024). A unique case is that of Trifyl, a public waste management authority in the Tarn department (Southwest France), which produces RDF by co-processing residuals from bulky waste sorting and the solid digestate of MSW anaerobic digestion. Following drying and sorting steps, two RDF streams are produced: (i) a high-calorific stream (16–20 MJ/kg) used by a nearby industrial plant and (ii) a lower-calorific stream (12–14 MJ/kg) used internally to heat anaerobic digesters and dry the solid digestate. Internal incineration generates approximately 6000 tonnes of bottom ash (IBA) per year, which are currently landfilled without valorization. This study was conducted within the framework of the ASHES program (Advanced Sampling for a Harmonized Environmental Solution), an academia-industry collaboration between the Earth Sciences Department of the University of Turin (Italy) and Alkaline Technologies (France). Over five months (January–June 2025), IBA samples (2–3 kg each) were collected monthly at the Trifyl WtE facility, yielding a total of ~10 kg. Samples were sealed immediately, then dried at 105 °C and sieved into four granulometric fractions: < 0.5 mm, 0.5–1 mm, 1–2 mm, and > 2 mm. The present study aims to explore the valorization potential of this novel typology of RDF bottom ash—particularly its CO_2 sequestration capacity, comparing to previous studies on RDF bottom ash carbonation (Baciocchi, et al., 2010). The potential of the IBA for enhanced metal recovery was also investigated through magnetic and density separation. Aqueous carbonation experiments were carried out in a 1.5 L double-walled Pyrex reactor equipped with high-precision gas flow sensors. Solid-liquid characterization includes optical microscopy, XRPD with Rietveld refinement, SEM-EDS, Ion Chromatography, ICP-MS, and XRF. Leaching behavior before and after treatment is evaluated through EN 12457-2 standardized tests. This poster presents the results of a study that offers a holistic physicochemical characterization of incinerator bottom ash produced from the incineration of refuse-derived fuel generated from the anaerobic digestion of municipal solid waste.

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Magnetic zeolite from wastes: extraction techniques for release of drugs after their adsorption from polluted water

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Keywords: waste, magnetic nanoparticle, ofloxacin.

Antibiotics and pharmaceuticals, in general, are widely used in public health to heal from various diseases. Once administered, most of these compounds are only partially metabolized, and may reach surface waters with the wastewater at low but potentially toxic concentrations. Antibiotics pose the most serious threat. Among the others, fluoroquinolone antibiotics (FQs) are the most commonly used, and almost 80% of them are discharged into the environment (Chen et al., 2019). In the last few years, it has therefore become mandatory to develop strategies to remove them using different processes including adsorption by natural or synthetic crystalline materials. Among minerals, numerous studies have documented the successful use of zeolites (Belviso et al., 2021). Due to their "open" structures characterized by framework of linked TO4 tetrahedra (T = Si, Al, or others), each consisting of four O atoms surrounding a cation, zeolites show many properties (e.g. high surface area and porosity), making them interesting materials also for water remediation by this type of organic pollutants.

In this study, magnetic zeolites formed from the combination of fly ash (FA) and Fe synthetic nanoparticles (FANPs1 and FANPs2) or mixtures of fly ash and red mud (RM) (FA1RM1 and FA4RM1) were used to remove ofloxacin (OFL), a fluoroquinolone antibiotic, from polluted water and their regeneration was investigated using three different techniques: ultrasound (UsAE), microwave (MwAE), and magnetic hyperthermia (MhAE) assisted extractions. FA and RM are waste materials resulting from coal combustion in thermoelectric power plants and alumina extraction from bauxite, respectively.

The results indicate that all the synthetic zeolites are efficient in OFL removal from polluted aqueous solution. Moreover, the data show that adsorbed antibiotic can be extracted from synthetic products and quantified using ultrasonic (about 50%), microwaves conventional processes (higher than 80%) and alternative magnetic hyperthermia method (about 60%).

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SEM characterization of K zeolite formed from combination of biomass (rise husk) and industrial waste (red mud)

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Keywords: biomass, red mud, merlinoite and chabazite intergrowth.

Biomass is a complex heterogeneous mixture of organic and inorganic matter. Such organic material is mainly represented by herbaceous agriculture waste such as grasses and flowers, straws, husks, pits (agriculture biomass). Rise husk (RH) is the natural sheath that forms on rice grains during their growth and thus it is an abundant waste byproduct of rice milling. The most dominant inorganic element identified in RH is amorphous silica thus making this waste material a potential source to produce synthetic zeolite.

Red mud (RM) is an industrial waste resulting from alumina production when the bauxite ores are subjected to caustic leaching. RM is generally characterized by the presence of iron oxy-hydroxides such as hematite and goethite with minor aluminium hydroxides (i.e., boehmite). The waste risk of RM is mainly due to high pH and alkalinity that could determine accumulative contamination of land and water.

In this work, mixtures of RH and RM were successfully used as unconventional sources of silica and alumina to form zeolites by KOH pre-fusion hydrothermal method at 90 °C. The morphological characterization of newly-formed materials was performed by using a Field Emission Scanning Electron Microscopy (FE-SEM) equipped with an energy dispersive spectrometer (EDS), thus observing the synthetic products at a very high resolution. The images show the formation of the typical bundle-like morphology of merlinoite with chabazite intergrowth.

Exchanging waste for feldspar: bone ashes in sanitaryware

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Keywords: feldspar, ceramic industry, waste valorization.

Feldspar is an important phase in ceramic industry, where it is added as a fluxing agent, to promote densification. In spite of being the most common minerals on Earth Crust, as a commodity, at a grade suitable for ceramic industry, feldspar is a critical raw material. This comes from the high dependence from import from Turkey, up to 43 % in Italy and 51% in the EU. Moreover, the price of feldspar has almost doubled between 2020 and 2024, after prolonged constant prices between 2002 and 2020. Exchange of feldspar with an alternative material, coming from end-of waste is therefore sought. In previous investigations the addition of up to 7% bottom ashes provided good results in terms of the rheological properties, at the expense of higher deflocculant addition; moreover the reference targets for water absorption and shrinkage were attained in a rather narrow temperature range. Addition of fired ceramic scraps to the mixture, hence reducing the need of feldspar, provides optimum performance, but the thermal expansion is lower than reference, due to the reduced quartz content.

Here we tested a new mixture, with animal bone ashes as a substituent for feldspar. At first 5 or 2.5% bone ashes were mixed with 25% Ball Clay, 25% China clay, 20% quartz and 25 or 27.5 % feldspar. The mix was shaped in a tile sized 25 cm2, and heated at 1220 °C in a ceramic route of 12 hours. Comparison with reference composition (with 30% feldspar), showed that the target water absorption is attained at lower temperature in samples with bone ashes (~15 °C), and that suitable results were obtained with just 2.5% bone ashes. To reduce further the feldspar content, quartz was increased, up to 29.5 %, with 2.5% bone ashes and 180% feldspar. This composition provides a match between reducing feldspar and attaining optimal conditions for the water absorption.

Further investigation is in progress to test body mechanical properties and thermal dilation behaviour, as well as to evaluate differences in its mineralogical composition and microstructure.

Thermal deactivation of asbestos-cement, recycling, eco-compatibility and sustainability

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Keywords: asbestos-cement, thermal inertization, recycling.

Asbestos-cement, i.e. the hazardous construction material still widespread in the built environment, can be efficiently deactivated by thermal processes and recycled in a variety of commodities as secondary raw material. Tests have been successfully conducted in sanitary ware ceramics, mortar, rockwool and polymers (including eco-friendly polylactic acid, PLA). Among these, the most promising concern: mortar, where up to 7 wt. % of deactivated asbestos cement (DAC) can be added without compromising the workability of the mixture and slightly improving the mechanical properties of the final product; epoxy resin, where up to 30 wt.% of DAC can be embedded improving hardness and wear resistance of the composite; stonewool, where a mixture of 50:50 diabase:DAC can be fiberized obtaining mechanical and thermodynamical properties comparable to commercial stonewool (Capitani et al., 2024a, 2024b and references therein). Additional tests are currently in progress with construction bricks, geopolymers and cement.

However, for a process to be upscaled at industrial level, safety of the deactivated asbestos cement and sustainability of the whole process have to be assessed. In this regard, the results of a recent study (Negri et al., 2025) about the effects of DAC on the soil ecosystem through the soil model organism *Folsomia candida* (Collembola), suggest that improper disposal or soil contamination by DAC may pose ecological risks, reinforcing the convincement that recycling DAC into stable matrices, such as ceramics or mortar, minimizes environmental contamination while promoting circular economy. Moreover, the results of life cycle assessment combined with cost–benefit analysis (Ferrini et al., 2024), suggest that deactivation technologies may represent a sustainable alternative to landfilling, although their success is dependent on securing public funding, a thorough examination of hidden environmental costs and risks, and the establishment of supportive regulations promoting circular economy. All together these findings suggest that the time is ripe to make asbestos treatment options a global reality.

Capitani G. et al. (2024a) - Recycling thermally deactivated asbestos cement in mortar: A possible route towards a rapid conclusion of the "asbestos problem". Journal of Environmental Management, 355, 120507, https://doi.org/10.1016/j.jenvman.2024.120507.

Capitani G. et al. (2024b) - Recycling thermally detoxified asbestos-cement in stone-wool: An end-less-life material! Construction and Building Materials, 440, 137351, https://doi.org/10.1016/j.conbuildmat.2024.137351.

Ferrini S. et al. (2024) - Assessing the economic impact of the thermal inertization of asbestos waste with an Italian case study. Academia Environmental Sciences and Sustainability, 1, https://doi.org/10.20935/AcadEnvSci7398.

Negri I. et al. (2025) - Ecotoxicological impact of deactivated asbestos-cement on soil ecosystems. Waste Management, 202, 114825, https://doi.org/10.1016/j.wasman.2025.114825.

Carbon dioxyde sequestration through natural carbonation of ladle furnace slag from northern Italy

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Keywords: steel slag, natural carbonation, lime.

Steel production in Italy takes place mainly in electric arc furnaces (EAF), where steel scrap is melted and then dephosphorised by the addition of lime, which is also used as a desulphurisation agent in the secondary refining process in the ladle furnace (LF). As a result, the steelmaking process produces the solid residues known as steel slag, which accounts for approximately 10-15% of crude steel production. Focusing on the LF slag, the large use of lime during the process results in a slag composed mainly of free calcium/magnesium oxide (f-CaO, f-MgO), calcium silicates (CS, C_2S and C_3S) and calcium silicate hydrate (C-S-H) gel (Wang et al., 2024). All of these minerals are conducive to CO_2 sequestration, allowing LF slag to be utilised as a potential CO_2 storage site via mineral carbonation (MC).

Dry carbonation is one of the least studied carbonation processes, but is the most comparable to natural carbonation. In this work, we sought to simulate the natural carbonation of LF slag by ageing the slags in an open environment protected from the elements. The set of LF slags studied is composed of five LF slags from different steel plants in Northern Italy and the work integrates the chemical composition with CO_2 content, mineral composition, thermogravimetric data and particle size at different stages of ageing. Therefore, the LF slags were also sieved at 1.0 mm at each ageing stage, with the lower fraction then being analysed.

On the basis of their chemical composition, the LF slags were classified into 2 different groups: Group A is characterised by a CaO+MgO content above 55.0 wt%, while Group B presents a CaO+MgO content below 52.0 wt%. The use of CaO+MgO as a discriminator is due to the propensity of the Ca and Mg minerals to carbonate, thus at first sight identifying Group A as the most likely to absorb more CO_2.

The CO_2 measured in each sample was normalised to the theoretical absorbable CO_2 of each sample based on the CaO and MgO content, taking into account that they could all potentially be mineralised in carbonates. A sample from group A shows the highest CO_2 uptake, both in the bulk fraction (684) and in the sieved fraction (684/01), which are 0.156 and 0.213 respectively (or 16.3% and 21.3% of the theoretical absorbable CO_2 of the sample), which can be explained by the high CaO content combined with the low SiO_2 and Fe_2O_3 content of the sample. On the other hand, the sample with the highest Fe_2O_3 content achieves a value of captured CO_2 of 0.070 of absorbed CO_2 in the bulk fraction (1034) and 0.150 in the fraction below 1.0 mm (1034/01), further confirmin the influence of the particle size on the carbonation process.

The analytical results confirm that the main factors influencing the natural dry carbonation of LF slag are the chemical composition, the mineral composition and the particle size, resulting in CO_2 sequestration that can partially offset the CO_2 process emissions of both lime and steel production.

Wang S. et al. (2024) - A Review on the Carbonation of Steel Slag: Properties, Mechanism, and Application. Materials, 17(9), 2066, https://doi.org/10.3390/ma17092066.

Phase evolution in thermally treated Construction and Demolition Waste (CDW): influence of chemical composition, temperature and dwell time

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Keywords: Construction and Demolition Waste, vitrification, waste management.

This study aims to investigate the effect of vitrification on Construction and Demolition Waste (CDW) from various disposal sites through specific thermal treatments, with the goal of transforming a heterogeneous waste into more homogeneous products with a glass-rich character. In fact, a novel approach to treating this waste is needed, as CDW currently represents a major waste stream, accounting for more than 30% of total waste in the European Union. In this perspective, EU directives aim to reduce landfilling in favour of recycling or even upcycling this waste.

CDW samples were obtained from different sites in charge of collecting demolition rubble after the 2016 earthquakes in Central Italy. The starting CDWs exhibit distinct chemical and mineralogical signatures. CDW.RAS and CDW.PRO contain, respectively, ~34 wt.% and ~35 wt.% SiO_2 and ~8 wt.% and ~7 wt.% Al_2O_3, higher than CDW.TAL, which shows only ~15 wt.% SiO_2 and ~3 wt.% Al_2O_3 . By contrast, CDW.TAL is significantly enriched in CaO (~39 wt.%) compared to ~29 wt.% in CDW.RAS and ~25 wt.% in CDW.PRO. These differences, despite the limited provenance area, reflect the heterogeneity of CDW, due to construction styles and ages, and different building materials used. These factors highly influence the separation process of the components and the possible recycling of CDW in the construction sector.

To perform the experiments (18 runs), CDW samples (with grainsize < 63 μm) were heated up to different target temperatures (*T*) of 1100, 1200, and 1300 °C and held isothermally for either 2 or 8 hours (*t*); the experimental run-products were rapidly quenched in a water bath to avoid further crystallization during the cooling process from high-*T* to room conditions.

The products resulting from the experiments were mineralogically and micro-chemically characterized by X-ray Powder Diffraction (XRPD) and Electron Microprobe Analysis (EMPA). Mineralogical assemblages of the treated samples were then evaluated as a function of the starting waste composition and the applied experimental conditions (*T* and *t*). From macroscopic and microstructural perspectives, increasing the thermal treatment temperature and holding time progressively vary the type and amount of crystalline fraction and promote particle welding, ultimately leading to homogeneous glass networks indicative of complete vitrification. The only deviation from this behaviour was observed in CDW.TAL. This resistance to complete welding and vitrification is likely due to its elevated CaO content, which promotes the stabilization of calcium-rich phases and hinders melt homogenization.

These findings demonstrate the feasibility of converting heterogeneous CDW streams into homogeneous, glass-like materials via controlled thermal treatments, with the CaO content playing a pivotal role in crystallization kinetics. Future work will be dedicated to comprehensive studies to ensure and define the potential application of the vitrified waste forms.

From rubble to resource: evaluating the recycling of CDW fine fractions in sustainable clinker blends

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Keywords: construction and demolition waste, recycling, clinker.

Construction and Demolition Waste (CDW) constitutes over one-third of the total waste generated in the European Union. The 2016 Central Italy earthquake further highlighted the urgency of identifying wider applications for CDW derived from rubble, as shown by previous studies (Galderisi et al., 2021). This study addresses the challenges posed by CDW disposal by promoting waste management strategies aligned with circular economy principles. The research specifically focuses on the characterization of unrecycled CDW, aiming to assess its feasibility as secondary raw material for clinker production in the cement industry.

Systematic CDW sampling was conducted across multiple disposal sites in the Central Italy earthquake zone, where < 63 μm fractions were selected for this study. A comprehensive suite of analytical techniques was employed to characterize the samples, including X–ray Powder Diffraction (XRPD), Scanning Electron Microscopy (SEM), Thermogravimetric Analysis (TGA), Inductively Coupled Plasma (ICP), Neutron Activation Analysis (NAA), and Hyperspectral Imaging (HSI). Leaching determinations were performed following the UNI EN 12457-2:2004 to qualify the cessation of waste status for inert construction and demolition waste. The chemical composition shows the presence of SiO_2 (15.89 wt.% – 35.84 wt.%), Al_2O_3 (3.41 – 8.89 wt.%), Fe_2O_3 (1.44 – 3.63 wt.%), MnO (0.06 – 0.09 wt.%), MgO (0.97 – 1.99 wt.%), CaO (25.23 – 39.31 wt.%), Na_2O (0.29 – 1.15 wt.%), K_2O (0.44 – 1.64 wt.%), TiO_2 (0.18 – 0.42 wt.%), P_2O_5 (0.10 – 0.24 wt.%), and Loss on Ignition (19.57 – 32.02 wt.%). The mineralogical analysis consistently revealed a predominance of calcite (27.7–66.9 wt.%), though in varying amounts, along with quartz (7.8–15.9 wt.%). Other detected phases included gypsum, feldspars, micas, and clay minerals. The amorphous content of the analyzed materials ranges between 43.5 wt.% and 56.1 wt.% Leaching tests have demonstrated that all examined elements are well within the limits established by current regulations, thereby confirming the environmental safety of these materials. Furthermore, hyperspectral imaging (HSI) analysis has verified that no asbestos fibers are present. The mineralogical and chemical composition of these CDW fractions suggests their potential use as ingredient in clinker manufacturing. Accordingly, a series of experimental formulations was developed to demonstrate the feasibility of this application. The tests were carried out using a base raw mix of clinker, consisting of limestone (49-45 wt.%) and CDW.MUS-63 (48-52 wt.%), with minor additions of a sludge from the glass-cutting process (~3 wt.%), which is rich in SiO_2 (36.14 wt.%), Al_2O_3 (19.87 wt.%), and Fe_2O_3 (34.98 wt.%). Each formulation was designed to maintain the key compositional parameters within optimal ranges for clinker production: Silica Ratio (SR) of 2.38, Alumina Ratio (AR) (1.46–1.50), and Lime Saturation Factor (LSF) (92–98%). The results demonstrate that CDW can be effectively used as secondary raw materials in the cement industry. Primarily, this approach supports the management of rubble generated by events such as the 2016 Central Italy earthquake, thereby contributing to the transition toward more environmentally sustainable industrial practices. Furthermore, the use of CDW and sludge from the glass-cutting process in clinker production enhances resource efficiency and reduces CO_2 emissions, in line with circular economy principles and broader sustainability goals.

Galderisi A. et al. (2021) - Petrography of construction and demolition waste (CDW) from Abruzzo region (Central Italy). Waste Management, 123, 456-465, https://doi.org/10.1016/j.wasman.2021.10.028.

Employing membrane technologies for Chromium removal from natural water resources

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Keywords: climate change, ungrafted grapevines.

A comprehensive and interdisciplinary study was undertaken to address the issue of chromium-rich groundwaters in the frame of the PNRR project (Spoke 1, Goal 2, PP2, Action 7). Specifically, the research combined a geochemical survey to map this contaminant's distribution across ophiolitic aquifers in the Lucania region (Southern Italy) with experimental tests employing membrane treatment. This latter approach represents an innovative and sustainable methodology for water purification (Figoli et al., 2016). A geochemical survey was conducted, and several water samples were collected. These samples were then characterized for their chromium content using an iCAP PRO XP Duo ICP-OES instrument. The analyzed waters exhibited varying levels of chromium, and those with the highest concentrations (M-type ~30µg/L Cr; P-type ~40µg/L Cr) were selected for subsequent treatment experiments. A laboratory-scale pilot system was utilized for these tests, and three nanofiltration membranes, which had not been previously evaluated for chromium removal from water, were chosen: Trisep TS80 (polyamide), Trisep TS40 (polypiperazine), and Trisep XN45 (polypiperazine) (from the Mann+Hummel group). The treatment tests were conducted at four different operating pressures: 3 bar, 6 bar, 9 bar, and 12 bar. The highest permeate flow rates were achieved with the Trisep XN45 membrane (average fluxes: 3 bar = 24.3 L/hm^2; 6 bar = 60.4 L/hm^2; 9 bar = 80.7 L/hm^2; 12 bar = 111.4 L/hm^2). Conversely, the Trisep TS80 membrane type showed the lowest permeate fluxes. The results of the analyses demonstrate that all the tested membranes effectively reduced chromium concentrations to below the legal limit. Considering the highest flux rates observed even at moderate operating pressures, coupled with the good ionic salinity after treatment, the Trisep XN45 membrane represents a promising candidate for in-situ applications by using a membrane prototype based on solar energy aimed at resolving environmental problems associated with chromium contamination in the pilot area.

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Figoli A. et al. (2016) - Membrane technologies for water treatment: removal of toxic trace elements with emphasis on arsenic, fluoride and uranium. CRC Press.

Valorization of white steel slags as a hydraulic binder

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Keywords: ladle steel slag, in-situ XRPD, waste valorization.

The utilization of industrial by-products as alternative raw materials represents an increasingly significant strategy for promoting sustainability in the construction sector. This study focuses on optimizing a cementitious mixture based on white steelmaking slag, a high-calcium and high-aluminum residue derived from steel production processes. Following the chemical and mineralogical characterization of the initial slag, various formulations were designed and tested using a Design of Experiment approach. These formulations varied in water content and inorganic admixtures, which were used to regulate setting time and paste workability. The mixtures were evaluated through compressive strength tests after 7 and 28 days of curing time. Laboratory investigations, conducted using in situ X-ray Powder Diffraction (XRPD) measurements, allowed for an in-depth analysis of the early hydration processes and phase evolution of the pastes at different curing times. The results demonstrate that the use of white slag enables the production of mixtures with good mechanical performance while simultaneously promoting the recovery of waste materials and the reduction of environmental impact.

Improved accuracy of Laser-Induced Breakdown Spectroscopy towards its application for in-line sorting of Construction & Demolition Waste (CDW) materials

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Keywords: construction and demolition wastes, National Institute of Standards and Technology, laser-induced breakdown spectroscopy.

Laser-Induced Breakdown Spectroscopy (LIBS) is recognized as an innovative analytical technique, used for rapid elemental analysis across a wide range of environmental samples (Zhang et al., 2021). LIBS technology is cost-effective, providing direct, rapid, on-site, and real-time measurements of target elements with minimal or no sample preparation, which appears as promising for in-line sorting of construction and demolition wastes (CDWs) (Chang et al. 2022). The present study aimed to improve the accuracy of portable LIBS technology to enhance elemental quantification in CDWs. Pressed powder pellets of certified reference materials from the National Institute of Standards and Technology (NIST) and different categories of mixed CDW samples (cements, concrete and masonry), previously analyzed by X-ray fluorescence (XRF), were measured by the SciAps Z900 handhold LIBS spectrometer. A total of about 80 samples were used to create a new standard calibration dataset. Matrix-matching calibration method of selected materials is built and used prior to LIBS analysis, following standard instrumental protocols. The new calibration method showed significant results with low matrix effects and minimal interference of analyte's signals from sample matrix. The NIST and CDW materials used for new calibration have wider Si contents and up to much higher Ca contents (from 20 to 70 wt % and from 10 to 75 wt %, respectively) than the certified standards used for the built-in SciAps "Geochem" calibration which makes the built-in calibration not enough accurate for analysis of CDWs. While results for most of the major elements (Si, Al, Ti, Fe, Mn, Mg, Na and K) show similar accuracy for the new and the built-in calibrations. The quantification of Ca is significantly improved from 13.9 (built-in) to 4.28 (new calibration) average relative differences. Our findings suggest that building a new matrix-matching calibration method in LIBS is more feasible to improve accuracy and precision of the measurements in similar and different matrices. The development of portable LIBS technology could serve as a viable alternative to conventional analytical techniques, by generating accurate calibration methods for high quality assurance with real-time measurements in laboratory and field settings.

Chang C. et al. (2022) - Cluster-based identification algorithm for in-line recycled concrete aggregates characterization using Laser-Induced Breakdown Spectroscopy (LIBS). Resour. Conserv. Recycl., 185, 106507, https://doi.org/10.1016/j.resconrec.2022.106507.

Zhang Y. et al. (2021) - Application of laser-induced breakdown spectroscopy (LIBS) in environmental monitoring. Spectrochim. Acta B: At. Spectrosc., 181, 106218, https://doi.org/10.1016/j.sab.2021.106218.

REEs and valuable metals recovery from the red muds of the Eurallumina site in Porto Vesme, Sardinia, Italy

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Keywords: Red Muds, REEs, critical raw materials.

Red Muds (RMs) or bauxite residues obtained by the Bayer process for alumina production are recognized to be a serious environmental hazard as well as a potential polymetallic source, as they are still rich in many valuable metals including rare earth elements (REEs), Sc, and Ga. To extract and recover the target elements from red mud the two essential steps are leaching/dissolution and recovery/adsorption from the leachate. The first leaching process evaluated is a sulfuric acid attack, while the recovery process is a solid-liquid adsorption onto sorbent substrates.

The above approach was applied to the red muds from Porto Vesme disposal site, that previously underwent geochemical and mineralogical characterization (Mameli et al. 2025, Schingaro et al., 2025). The mineralogical composition includes hematite, goethite, ilmenite, gibbsite, boehmite, bayerite, anatase, rutile, quartz, sodalite, cancrinite, garnet, halite and a variable number of minor phases whereas geochemical analyses evidenced valuable critical transition metals and rare earth elements (REEs) associated to zircon (Hf), phosphate (Y) or ferrotitanate (LREEs).

The leaching process was carried out through an acid attack with sulfuric acid, with the addition of hydrogen peroxide to suppress silica gel formation and allow the operation at a lower liquid to solid ratio (higher pulp concentration). The initial experiments show that the best operative conditions are high temperature and leaching agents concentration of 1M or 2M. No silica gel formation is observed at liquid to solid ratio of 10, while at a liquid to solid ratio of 5 silica gel forms after 2 hours of leaching.

Recovery efficiencies vary for the different elements, from 70 to 90% (Sc, Ga) to 30 to 40% (La, V, Ce) to 15% (Y). The efficiency of recovery of the target elements improves when operating at a higher temperature, while the effect of the leaching agent concentration is only minor.

Among the sorbent substrates initially tested, the best performances are obtained for materials derived from the alkaline activation of ladle steel slags. With these materials the adsorption efficiency remained higher than 60% (90% in the best case) for initial pulp concentrations up to 0.3 gCu/gsorbent.

Mameli P. et al (2025) - Distribution and fractionation of Rare Earths (La–Lu, Sc, Y) and other critical metals in bauxite residues: addressing the profitability of the red muds stored at the Porto Vesme disposal site, Sardinia Island, Italy J. Geochem. Explor., 275, 107792, https://doi.org/10.1016/j.gexplo.2025.107792.

Schingaro E. et al. (2025) - Exploring the potential of red muds from Portovesme (SW Sardinia, Italy): Multiscale analysis of REEs content and mineralogy, Heliyon, 11, e43303, https://doi.org/10.1016/j.heliyon.2025.e43303.

From waste to construction: quartzite waste paving the road of recycling

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Keywords: quartzite, stone waste recycling, cementitious tile adhesives.

Waste generated from the quarrying of heritage stones, which play a significant role in various social and economic applications, largely retains the mineralogical and compositional properties of the original stone, despite the risk of pollution from tool wear during extraction. This study aimed at evaluating the feasibility of recycling quartzite waste as fine and ultra-fine aggregate in the production of cementitious adhesives for tiles, in accordance with UNI EN 8520-1 (2005). Analyses including particle size distribution, X-ray diffractometry (XRD), X-ray fluorescence (XRF), and Scanning Electron Microscopy (SEM) were conducted to thoroughly characterize the waste material. The experimental procedure involved designing three different adhesive formulations, each tested with various tile types to assess their grip performance. Fresh doughs were tested for reology and cured for normative requested time after being stuck on a concrete support as reported in standards (UNI EN 12004-2, 2017). The technical performance of the adhesives was measured through the Pull-Off test, allowing to acquire data for high initial tensile adhesive strength in accordance with UNI EN 12004-1 and UNI EN 12004-2 (2017).The results confirm that quartzite waste from the Indian stone industry can be used as cementitious adhesives without compromising technical performance, offering a promising alternative to landfill disposal for this type of industrial by-product.

UNI EN 8520-1 (2005) - Concrete aggregates. Supplementary instructions for the application of EN 12620 - Part 1: Designation and conformity criteria.

UNI EN 12004-1 (2017) - UNI EN 12004-1. Adhesives for ceramic tiles - Part 1: Requirements, assessment and verification of constancy of performance, classification and marking.

UNI EN 12004-2 (2017) - UNI EN 12004-2. Adhesives for ceramic tiles - Part 2: Test methods.

Sustainable porcelain stoneware: valorisation of CDW fines in ceramic body formulations.

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Keywords: porcelain stoneware, sustainable ceramics, secondary raw materials.

The construction sector produces large volumes of construction and demolition waste (CDW), presenting environmental concerns and sustainable resource recovery opportunities. This study explores the valorisation of CDW fines as partial replacements for traditional raw materials in porcelain stoneware tile production, contributing to circular economy strategies in the ceramic industry. CDW fines from two different sources were selected, each exhibiting distinct mineralogical compositions, particularly in terms of calcite content. Detailed physicochemical characterisation was conducted to assess their suitability for ceramic applications. X-ray diffraction (XRD), X-ray fluorescence (XRF), and particle size analysis revealed that both materials are composed predominantly of quartz and plagioclase, with varying proportions of calcite. These mineralogical traits suggest a potential role for the CDW fines as feldspar substitutes, with the added benefit of enhancing the plasticity and sintering behaviour of the ceramic bodies. Based on these findings, a feasibility study was carried out to integrate different percentages of CDW fines into an industrial porcelain stoneware formulation. Test specimens were prepared, dried, and fired at temperatures ranging from 1180 °C to 1220 °C. The fired samples were evaluated for key performance indicators, including bulk density, water absorption, and mechanical strength, following standard protocols. In addition, scanning electron microscopy (SEM) was used to observe microstructural features such as pore morphology and vitrification. Preliminary results indicate that the incorporation of 5 to 8% CDW fines is technically viable, with final properties meeting the requirements for porcelain stoneware tiles, i.e., water absorption < 0.5% and bulk density 2.36 g/cm^3. This research demonstrates the potential for converting heterogeneous CDW fines into valuable secondary raw materials for high-performance ceramic products, supporting environmental and industrial sustainability objectives.

Valorization of hydrothermally treated sewage sludge in clay brick production: microstructural characterization and porosity analysis

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Keywords: sewage sludge, hydrothermal process, clay ceramics.

The valorization of waste materials in ceramic production presents a novel approach to conserve primary geological resources while reducing the environmental impact of sludge disposal, therefore supporting sustainable development strategies. In this study, we investigate the incorporation of hydrothermally treated sewage sludge into traditional clay-based ceramic bodies for brick manufacturing. The present study concentrates on the microstructure, with particular emphasis on porosity, considering the potential applications of such bricks, which seek to address the challenges of sustainability and environmental responsibility.

The hydrothermal treatment of diluted sewage sludge was carried out at the FREEDOM demonstration plant, in Cassano D'Adda (MI), under conditions defined based on literature studies (Wang et al., 2014; Ningbo et al., 2019). This process consisted of a temperature of 220 °C for a duration of 30 minutes, with pre-heating and cooling times of 20 minutes each. The obtained product was subjected to a mechanical filter to separate the liquid phase from the solid phase, hereafter referred to as "cake". The clay used in this study was quarried at Cascina Groppello (Valenza, Italy). Chemical analyses were carried out by XRF. The minerals forming the material are quartz, albite, microcline and muscovite. The measured chemical and mineralogical compositions agree with the literature data on clays in the Piedmont basin area (Dondi et al., 1999a; 1999b).

The sintering behaviour was investigated on samples prepared by replacing 10, 30 and 50 wt% of the illitic clay with the cake and heat-treated at 900 °C, in an industrial kiln.

Microstructural characterization was conducted using scanning electron microscopy (SEM), with complementary three-dimensional imaging via X-ray microtomography (XRCT). To provide a more detailed description of the samples, SEM observations were conducted with a focus on characteristic features, including clasts/grains, matrix, and porosity.

The bulk density of the ceramics significantly decreases as the amount of biosolid increases, due to the porosity induced by thermal decomposition of organic matter. The real density of the material, however, differs noticeably from the apparent density and rises as the amount of cake in the samples increases, according to data from the N_2 gas pycnometer and Hg intrusion porosimetry. The presence of ceramic bridges built of calcium iron phosphate derived from the biosolid may indicate a higher degree of sintering of the material, which could explain the increase in real density. Using micro-CT in conjunction with 3D image analysis, the porosity and pore systems in the synthesized bricks were more thoroughly assessed.

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Dondi M. et al. (1999b) - Major deposits of brick clays in Italy. Part 2: Technological properties and uses, 15, 360-370.

Ningbo G. et al. (2019) - A new method combining hydrothermal carbonization and mechanical compression in-situ for sewage sludge dewatering: Bench-scale verification. J. Anal. Appl. Pyrolysis, 139, 187-195, https://doi.org/10.1016/j.jaap.2019.02.003.

Wang L. et al. (2014) - Hydrothermal treatment coupled with mechanical expression at increased temperature for excess sludge dewatering: Influence of operating conditions and the process energetics. Water Res., 65, 85-97, https://doi.org/10.1016/j.watres.2014.07.020.

Assessing the CO_2 mitigation potential of alkaline solid waste mineralization under ambient conditions

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Keywords: waste carbonation, solid waste, carbon capture utilisation and storage.

Using industrial solid waste for CO_2 mineralization offers a promising avenue for advancing waste disposal while combating global CO_2 emissions. This strategy can remove CO_2 from the atmosphere or industrial gases and store it in the form of stable carbonate minerals, such as calcite ($CaCO_3$) or magnesite ($MgCO_3$). Although previous assessments suggest that up to 300 Mt CO_2 yr^{-1} could be sequestered globally through this method (Pan et al., 2020), such estimates are often based on generalized assumptions that may not fully capture the complexity of mineralogical compositions and carbonation kinetics (Zhang et al., 2024). In particular, the heterogeneous nature of industrial waste streams and the different reactivity of their constituent phases are areas that warrant further detailed investigation, as they may influence the accuracy of large-scale projections (Walker et al., 2024).

In this study, we evaluate the CO_2 reduction potential of several representative industrial solid wastes under atmospheric temperature and pressure, for instance, mine tailings, steel slag, red mud, coal fly ash, construction demolition waste, municipal solid waste incineration fly ash. We find that carbonation efficiency is dominantly governed by the abundance and reactivity of active and amorphous phases, which provide readily available Ca and Mg for carbonation. Under such alkaline conditions due to the dissolution of active and amorphous phases, the solubility of sulphates, such as gypsum and anhydrite, are also enhanced, enabling them to serve as additional sources of Ca for carbonates precipitation. In contrast, silicates contribute to carbonation more slowly, while inert phases show negligible reactivity. Through the integrated mineralogical and thermochemical analyses to the carbonated materials, we thereby develop a quantitative framework to assess the phase-specific contribution of Ca and Mg to overall CO_2 uptake. This approach reveals substantial variability in sequestration potential across different waste types, even when their bulk elemental compositions appear similar. These results highlight the importance of considering not just total oxide contents, but also the mineralogical form and reactivity of Ca- and Mg-bearing phases when evaluating CO_2 reduction potential.

Our findings emphasize the need to move beyond bulk oxide composition and toward a phase-specific understanding of carbonation potential, which more accurately reflects the true reactivity of industrial wastes. A more realistic, data-driven assessment is necessary to better guide both technological development and policy decisions for effective carbon sequestration through industrial solid waste. The obtained insights help to advance sustainable pathways for waste valorisation and climate change mitigation.

Pan S. et al. (2020) - CO_2 mineralization and utilization by alkaline solid wastes for potential carbon reduction. Nature Sustainability, 3(5), 399-405, https://doi.org/10.1038/s41893-020-0486-9.

Walker I. et al. (2024) - Mineralization of alkaline waste for CCUS. Npj Materials Sustainability, 2(1), 1-17, https://doi.org/10.1038/s44296-024-00031-x.

Zhang, Q. et al. (2024) - Assessment method of carbonation degree and activity of a wide range of calcium/magnesium containing solids. Journal of Cleaner Production, 467, 143009, https://doi.org/10.1016/J.JCLEPRO.2024.143009.

From shell waste to skincare: a circular economy approach using *Donax trunculus*

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Keywords: molluscs shell waste, circular economy, cosmetics.

Food production has a significant impact on the environment due to the high consumption of natural resources. Total fisheries and aquaculture production reached a record 223 million tonnes in 2022 (FAO, 2022), with the increase primarily driven by aquaculture, while capture fisheries production remained stable. Molluscs in particular play an important role in the aquaculture sector, generating around 10 million tonnes of shell waste per year. This biomineral waste, if not properly managed, can lead to disposal challenges and environmental impacts.

To mitigate these impacts, numerous management strategies for shellfish waste have been explored, ranging from applications in the chemical industry to innovations in building and construction materials. The study presented here outlines a detailed process for the conversion of *Donax trunculus* shell waste into mechanical abrasives suitable for cosmetic use. The process began with a market survey and analysis of commercial exfoliating cosmetic products to define the required physical and granulometric characteristics of the abrasives.

Our shell samples were subjected to cleaning protocols to remove organic residues and to variable grinding operations. Mineralogical and microstructural characterisation was carried out using X-ray diffraction (XRD), scanning electron microscopy (SEM) and infrared (IR) spectroscopy to assess the material composition and surface properties.

Finally, a series of granulometric tests were carried out to determine the optimal particle size distribution for cosmetic formulations. This valorisation strategy highlights the potential of *Donax trunculus* shells as a sustainable raw material and supports the development of greener alternatives in the personal care industry. The results of this research contribute to wider environmental sustainability efforts by promoting innovative uses of aquaculture by-products.

FAO (2022) - World Food and Agriculture – Statistical Yearbook 2022. Rome, https://doi.org/10.4060/cc2211en.

Enhancing road pavement stability with supplementary cementitious materials

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Keywords: supplementary cementitious materials, composite cement, roads stabilization.

The incorporation of supplementary cementitious materials (SCMs) as partial replacements for conventional Portland cement has emerged as a practical and immediate strategy for reducing carbon dioxide (CO_2) emissions linked to cement production. In light of the urgent need to make construction practices more sustainable, this study investigates the development of alternative, low-cement binder systems intended for use in the sub-base layers of road infrastructure.

To achieve this, the research involved designing and formulating a range of binary, ternary, and quaternary binder mixtures. These mixes were based on traditional Portland cement, combined with various SCMs sourced locally. Specifically, the materials used included fly ash derived from the combustion of woody biomass, bottom ash obtained from the incineration of municipal solid waste, and recycled concrete aggregates originating from construction and demolition waste. For the sake of comparison and benchmarking, reference mixtures composed solely of standard Portland cement were also prepared and tested.

In the initial phase of the study, the SCMs were thoroughly characterized to determine their chemical composition and potential for hydraulic or pozzolanic activity—key properties that indicate their suitability for use as active binder components. Once characterized, the next step involved examining the hydration behavior of the newly formulated cementitious systems. This was accomplished using a suite of analytical techniques including isothermal calorimetry (to monitor heat evolution during hydration), X-ray diffraction (to identify crystalline hydration products), and thermogravimetric analysis (to track mass changes associated with hydration reactions).

The hydration studies yielded compelling findings. In particular, the binary mixtures that incorporated either biomass ash or municipal incinerator ash demonstrated a marked increase in reactivity, as well as the formation of novel cementitious phases not typically found in conventional systems. Conversely, mixtures that included recycled concrete showed comparatively low reactivity, indicating limited potential for chemical bonding or strength development. Interestingly, the binary mix containing incinerator ash also exhibited a slower rate of hydration, which is likely attributable to the presence of residual organic matter interfering with the setting process.

As a final step, the most promising and reactive binary mixtures—specifically those formulated with biomass ash or incinerator ash—were combined with sandy soil in order to evaluate their performance as binding agents in geotechnical applications. This was done through unconfined compressive strength testing, which revealed that these mixtures possess encouraging cementing capabilities, potentially making them suitable candidates for sustainable road base construction.

Recycling waste materials for road subgrade stabilization: a cement-free approach

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Keywords: supplementary cementitious materials, free-cement binders, roads stabilization.

The foundation layers in road pavements play a key role in distributing external loads from the surface to the subgrade. When the subgrade exhibits low load-bearing capacity and significant volumetric instability, structural failures such as cracking and deformation can occur. In many construction scenarios, avoiding weak or incoherent soils is not feasible, and these do not typically meet technical requirements for bearing capacity. Cement is often used as a stabilising agent to improve their geotechnical properties. However, cement production is highly energy-intensive and is a major contributor to global CO_2 emissions.

Simultaneously, the extraction of natural aggregates from quarries is becoming less sustainable due to environmental degradation and increasing costs, especially when quarries are located far from construction sites. Therefore, the development of alternative binders based on industrial by-products and natural pozzolanic materials offers a promising approach to reduce the environmental footprint of soil stabilisation practices.

This study investigates the potential for total replacement of Portland cement (PC) in road subgrade stabilisation using combinations of natural pozzolan (NP) or metakaolin (MK) with secondary cementitious materials (SCMs), specifically wood biomass ash (BA), municipal solid waste incinerator bottom ash (MSWI), calcined concrete demolition waste (cCDW), and non-calcined concrete demolition waste (CDW). All materials were sourced from industrial processes and construction waste streams in Italy. The objective was to formulate low-CO_2 binders with high recycled content for use in foundation layers.

In the first stage, the physical, chemical and mineralogical characteristics of the selected waste materials were analysed, and their pozzolanic activity was assessed using the R3 test. In the second stage, binary and ternary binder systems based on MK or NP and SCMs were prepared and cured at different intervals. The hydration behaviour and phase evolution were characterised by X-ray diffraction (quantitative and qualitative analysis via Profex), thermogravimetric analysis, and isothermal calorimetry.

The calorimetric results revealed that BA and MSWI exhibited higher reactivity compared to CDW. However, BA required additional aluminosilicate sources to promote the formation of hydration phases. After 28 curing days, the MK-based blends containing BA and cCDW showed cementitious phase contents of 26.8% and 40.3%, respectively, while NP-based blends reached 24.2% and 38.2%. MSWI and CDW alone demonstrated limited pozzolanic reactivity. The most promising formulations are currently being validated through Proctor compaction and unconfined compressive strength tests.

Simple and effective characterization of incinerator bottom ash for metal speciation, hazardous waste classification and its recycling

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Keywords: bottom ash, hazardous waste classification, recycling potential

Bottom ash (BA) is the solid residue generated from municipal solid waste incineration. Its detailed physicochemical characterization is a crucial step to ensure proper classification according to current legislation (DL 152/2006; Reg. CE 1907/2006; UNI 10802:2014), as well as to determine its suitability for safe disposal or potential recycling. Traditional bulk chemical analysis, typically performed on acid-digested, untreated, and unsorted BA samples, provides information about the total concentrations of metals present. However, this approach fails to reveal how metals are actually bound within the matrix (e.g., as salts, oxides, silicates, or alloys). As a result, there is often a misinterpretation of heavy metal speciation—particularly for elements like Zn—which are frequently and erroneously assumed to be present in their most hazardous forms, such as oxides. This mischaracterization can lead to incorrect classification as hazardous waste, significantly limiting the recycling potential of BA.

In the case study presented here, the BA sample consists of a heterogeneous mixture including metal fragments, small glass beads ($f < 15$ μm), plastic residues, and traces of organic matter. Bulk chemical analysis indicated that Zn concentrations exceed the regulatory limits set by DL 152/2006, initially suggesting a hazardous classification.

To address this, we developed an integrated multi-technique characterization strategy. BA fractions were first separated by density using LST Fastfloat. Subsequently, each fraction was analyzed using a combination of Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Light fractions primarily consisted of plastics and organic matter, while heavier fractions were enriched in glass and metallic components. ICP-OES confirmed that metal concentrations were significantly higher in the heavy fraction. SEM-EDS further revealed that Zn was mainly hosted in Fe-Al alloys and in some silicate-based glass beads, rather than as ZnO.

These findings demonstrate that the actual speciation of Zn and other metals is less hazardous than initially assessed. Both metallic and glass fractions can be selectively recovered and recycled using a relatively simple density separation process. The proposed approach allows for more accurate classification and valorization of BA, overcoming the limitations of conventional analyses and supporting a more sustainable and resource-efficient management of post-incineration residues.

Characterisations and sorting of heterogeneous CDW (Construction and Demolition Waste): from lab to plant

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Keywords: CDW (construction and demolition waste), sorting, vibrational spectroscopy.

Waste materials from construction and demolition works are the largest by weight and volume. In UE, this accounts for about 36% of the total waste generated yearly by every European citizen (Eurostat report, 2020). Several Member States tackled the problem by implementing recovery policies and enforcing the reuse of secondary raw materials in public procurement (e.g., Italian D.lgs. n. 221/2015 – CAM). Traditional CDW recovery and processing consist of manual segregation of non-lithic fraction from the ceramic-like part (identified by the CER code 17.01) followed by crushing and sieving. Sorting by crystal-chemistry and/or physical properties (colour, porosity, compressibility, etc.) is lacking.

This approach prevents the separation of homogeneous groups of materials with constant and standardised properties, similar to the natural counterpart raw resources. Indeed, heterogeneous CDW are largely reused in downcycling applications. Therefore, CDW sorting is paramount for upcycling reuses (Galdersi et al., 2023) and for substituting, partially or entirely, natural raw georesources. Also, CDW commercial types and relative fractions (e.g. concretes, mortars, natural stones, bricks, roof tiles, tiles, etc.) can strongly differ from different areas as a function of lithology, architectural styles and regulations.

Similarly to rocks in nature, a complete and detailed set of characterisations of a CDW can be attained by several routine analytical methods, such as XRF, XRPD, optical microscopy, SEM and/or EPMA. However, these methods are extremely time-consuming due to specimen preparation and analysis and thus are hardly transferable at an industrial level. Conversely, vibrational spectroscopy can recognise the different types of CDW materials (Radica et al., 2024) rapidly and even on unprepared samples. Here, we present a set of referenced CDW materials with known crystal-chemical, petrographic and physical-mechanical attributes; the same samples are also rapidly characterised by IR vibrational spectroscopic methods under reflection mode to show limitations and advantages for the potential identification of the various CDW materials. This approach paves the way for a future transfer from the lab to industrial plants.

European Statistics-Eurostat. (2020) - Energy, transport and environment statistics 2020 edition. In Printed by Imprimeries Bietlot Freres, Belgium- Statistical Books, https://ec.europa.eu/eurostat/about/policies/copyright.

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Radica F. et al. (2024) - Characterization of CDW types by NIR spectroscopy: Towards an automatic selection of recycled aggregates. Journal of Building Engineering, 88, 109005, https://doi.org/10.1016/j.jobe.2024.109005.

Development of hydrometallurgical processes for the recovery of critical and precious metals from industrial waste

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Keywords: urban mining, waste, recovery.

The growing demand for critical and precious metals, alongside increasing environmental and geopolitical pressures, has spurred the development of sustainable and circular approaches to resource recovery. This doctoral research investigates the design, optimization, and implementation of hydrometallurgical and electrochemical processes for the selective recovery of valuable and criticals elements from different industrial and electronic waste streams. The study places particular emphasis on the use of organic acids, such as tartaric acid sourced from agri-food waste, as environmentally leaching agents. By integrating advanced experimental design methodologies with a suite of analytical techniques—including ICP-OES, XRD, XAS, and SEM-EDX—the research aims to enhance both the efficiency and the sustainability of metal recovery processes. Three representative case studies are presented: the closed-loop recovery of lithium from spent $LiFePO_4$ batteries, the extraction of molybdenum from used catalytic materials, and the recovery of silver from end-of-life photovoltaic panels. The findings contribute to the advancement of eco-innovative recycling strategies and underscore the potential of green hydrometallurgy within the framework of a circular economy.

The influence of cooling rate on the production of glass-ceramic materials from slag and glass waste

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Keywords: recycling glass, metallic waste, cooling rate.

Float glass and slag waste were mixed in 30 to 70 vol. % proportions, respectively, melted and solidified applying two different cooling rates to produce new glass-ceramic materials. The starting recycled glass has SiO2, Al2O3, Fe2O3, CaO, K2O and Na2O content of 69.81, 1.86, 0.42, 8.97, 2.06 and 11.68 wt.%, respectively, while the slag waste is iron-rich, i.e. Fe2O3 ~ 51 wt.%, with SiO2 and Al2O3, ZnO, CaO, and CuO content of 32.13, 4.77, 4.62, 3.43 and 0.81 wt.%, respectively. The powdered mix was first heated up to 1550 °C under air conditions and then rapidly quenched (after a dwell time of 4 h) to obtain a uniform glass. This recycled glass was successively re-heated up to 1550 °C, kept at this temperature for 0.3 h and finally cooled at rates of 10 (low) and 500 (high) °C/h down to low-*T*.

According to XRPD, SEM and EPMA characterisations, the two produced glass-ceramics contain mainly spinel crystals in a glassy matrix, but their textural features are variable in response to the low/high experienced cooling rates. The obtained glass-ceramics solidified at 10 and 500 °C/h produced 13.7 ± 2.2 and 30.0 ± 5.5 area% of spinel, respectively; unexpectedly, the 500 °C/h rate produced more crystals than the lower one. Nonetheless, spinels cristallized at 10 °C/h are either skeletal (relatively large crystals) or dendritic (tiny and short); conversely, at 500 °C/h they form only long dendrites (spinifex texture with a fern-like appearance) with sizes ranging from 10 to 60 μm. Furthermore, at 10 °C/h, the produced spinels are richer in Fe and Zn than at 500 °C/h.

These results indicate that cooling rates and industrial waste can be used to concentrate certain elements in easily separable spinels or to design glass ceramics with tuneable macroscopic features (optical, electronic, magnetic, etc.) without using additives, solutions or fluxing agents.

This work paves the way to an alternative scalable route for the recycling of industrial waste to produce artificial ore-bodies and/or new glass-ceramic materials.

Recycling of thermally transformed cement–asbestos for the production of concrete: towards a sustainable solution to the 'asbestos problem'

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Keywords: asbestos cement, thermal transformation, recycling.

The thermal transformation of asbestos-containing materials and the recycling of the product is a sustainable alternative to landfill disposal as an example of "end-of-waste" process in compliance with the European Community directives. In this study, "inactivated" asbestos-containing waste was introduced in concrete, by replacing increasing amounts of CEM II/A-L 42.5 R cement (from 5 to 15 wt.%) in the mix, with the twofold advantage of mitigate the environmental footprint of the building material and realize a real recycling opportunity for the waste. This work has been carried out in the framework of the PEGASUS project (POR CALABRIA FESR-FSE 2014-2020 funds), focused on the replacement of asbestos cement rooftiles and the concomitant implementation of a photovoltaic system in order to create a Renewable Energy Community. Owing to its content in C2S, a phase exhibiting hydraulic reactivity, the obtained concrete exhibited comparable or better mechanical performance (+1.8 MPa compressive strength, +1.4 MPa flexural strength for 15 wt.% replacement) with respect to standard concrete at 90 d and similar rheology/workability (class S2).

These results were ascribed to the increased fineness and high C2S content of the binder, leading to a behaviour similar to that of belite cement mixes, consistently with the phase composition and the recorded heat of hydration. The ability of C2S to react to a higher extent, producing more C–S–H compared to C3S, was considered crucial to the strength development. The sustainability of such 'end of waste' process has been assessed through a Life Cycle Assessment, which showed that, while thermal transformation has higher environmental impacts compared to other scenarios because highly energy demanding, recycling 15 wt.% of the waste into the cement reduces the environmental impact by 2.5% compared to neat cement. Reasonably, this gap could grow with the increase in efficiency of the process of thermal transformation in view of its upscaling.

Investigating the potential of marine extremophiles for biomining and bioremediation

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Keywords: marine bacteria, spent car catalysts, calcium carbonate.

Marine sediments, especially those marked by geochemical anomalies, represent underexplored reservoirs of microbes with potential applications in transforming waste into geo-resources. Our group isolated and tested bacterial strains to identify good candidates for innovation in mining and remediation, particularly utilizing microorganisms exhibiting resistance to Potentially Toxic Elements (PTE) and/or preference towards precious elements at high concentrations in the environmental matrix considered.

By integrating microbiological and geochemical methods, we aim to develop alternative strategies for biomining and bioremediation (Funari et al., 2019). We identified Spent Automotive Catalytic Converters (SACC), an increasing category of waste exhibiting high value and a source of supply of Platinum Group Elements (PGE), as a target sample. The bacteria were isolated through enrichment with SACC powder, thus favouring the selection of strains tolerant to the SACC (and its leachable elemental fraction). The isolation resulted in 24 strains from the main inlet of the Sarno River capable of high resistance. The pH tolerance test spotted two acidophilic strains, which can be more promising for leaching processes than alkalophiles (Karim & Ting, 2021). Selected strains' tolerance toward Pt(II), As(III), Zn(II), Pb(II), and Cd(II) was further evaluated to define the tolerance threshold of named species. Bioleaching experiments were conducted on the SACC, stressing the difference between the uses of SACC sonicated vs not sonicated to evaluate upscaling opportunities. Pt bioleaching efficiency was 27.3%, with the best candidate at circumneutral pH. In biorecovery experiments, strains were cultivated with Pt(II) doping, and the Pt yield was 92% with the best candidate.

Marine microorganisms were also tested for PTE bioremediation by promoting mineralization of PTE-bearing carbonate bio-minerals using Microbial Induced Carbonate Precipitation (MICP) mechanisms (Dhami et al., 2013; Vincent et al., 2022). In search of efficient bacteria, we evaluated the MICP potential of Lysinibacillus sphaericus PG22, a marine gram-positive sporulating bacterium isolated from N-Tyrrhenian sediments. Genome analysis revealed the presence of urease and metal resistance genes, confirming its ability to tolerate 1600 ppm $Pb(NO_3)_2$, and its ureolytic activity leading to the biomineralization of 61.7 g/l $CaCO_3$. TGA, XRD, and ESEM-EDX analyses proved the formation of calcite polymorphs already within 16 h of incubation. With the presence of Pb^{2+} in the test solution, PG22 promoted the formation of $PbCO_3$ and $Pb_3(CO_3)_2(OH)_2$, biomineralizing 98% of available Pb. These findings highlight PG22's potential for MICP-based strategies, offering a sustainable solution to restore marine and other contaminated environments.

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When green is not so green…

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Keywords: wind turbine blades, waste recycling, new materials.

Wind turbines have consistently been employed to generate renewable energy for already two decades and EU set a target to cover at least 32% of its energy needs with renewables by 2030. However, increased turbine installation also leads to growing waste. With a typical 20-year lifespan, many turbines installed since the 1990s are now reaching end-of-life. Turbines are largely recyclable, especially metals like steel, iron, aluminium, and copper. However, turbine blades (about 10% of the total mass) are more problematic. Made mostly from glass fibre reinforced polymers, these thermoset composites are difficult to recycle due to their crosslinked structure. While overall recyclability is around 85–90%, blades often end up in landfills or are incinerated. Recycling options include mechanical, chemical, and thermal methods like pyrolysis, but each has limitations. Developing effective blade recycling technologies is critical to fully realising wind energy's environmental benefits.

The aim of this study was to test the possibility to integrate the wind blade waste in a material retaining acceptable performance for practical applications, like for example in the building industry. The focus was on wind blade trimmings, to be inserted into geopolymers-based binders, thus avoiding the use of cement-based binders, reducing CO_2 production. The insertion of other types of waste, mixed to the wind blade waste, allows also to maximize the sustainability of the recycling process.

Geopolymers binders have been obtained by mixing metakaolin, K-silicate and quartz sand, to which wind blade granular (epoxy resin adhesive) and fibrous fractions have been added up to a content of almost 36 wt.%, using different proportions of the two. The samples have been characterized through physical/mechanical tests as well as SEM microchemical analyses and imaging. In particular, compressive strength reached values in the range 60.3-72.5 MPa, whereas flexural strength increased from 5 to 14.3 MPa when substituting the granular fraction with the fibrous one. Moreover, a prototype sample composed of almost 80wt% waste materials (using a mixture of fly ash, quartz-composite waste, and both wind blade waste fractions) still achieved about 11 and 50 MPa in flexural and compressive strength respectively.

By designing a performing sustainable material incorporating composite waste, this study puts forward wind blade waste as a secondary raw material hence providing a basis to tackle the increasingly important issue of composite waste disposal. Composite waste can be integrated in various proportions into building materials while still achieving high mechanical performance, avoiding both disposal costs and additional pollution therefore proving to be suited for the realization of sustainable materials.

Potential of bottom ash fine fractions for coupled enhanced metal recovery and accelerated carbonation

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Keywords: bottom ash, metal recovery, carbonation.

Incineration bottom ash (IBA) fine fractions (< 2 mm) continue to pose challenges for waste management, despite their recognized potential for enhanced metal recovery (EMR) and accelerated carbonation technology (ACT) (Costa et al., 2020; Schnabel et al., 2021; Pienkoß, et al., 2022). This work was conducted within the Advanced Sampling for a Harmonized Environmental Solution (ASHES) program, an academia–industry partnership between the Earth Sciences Department of Turin (Italy) and Alkaline Technologies (France). The novelty of the project lies in coupling metal separation techniques (magnetic and density-based) with liquid-phase carbonation, and in developing a geochemical database to track IBA heterogeneity. A 30 kg batch of IBA was collected from the top of the heap at a French waste-to-energy plant processing both municipal solid waste (MSW) and refuse-derived fuel (RDF). The ash was sealed immediately after sampling, and analyses were performed shortly after to capture early-stage reactivity. CO_2 (99.9% purity, Sapio) and ultrapure, degassed water were used throughout. IBA were dried at 105 °C and sieved into five fractions: < 0.25 mm (ultrafine, UF), 0.25–0.5 mm, 0.5–0.71 mm, 0.71–1 mm, and 1–2 mm. Three experiments were conducted per fraction (15 total): (i) direct carbonation, (ii) magnetic separation followed by carbonation, and (iii) magnetic + density separation followed by carbonation. Manual separations were performed using a laboratory magnetic wand and a black gold pan (38.5 × 8.5 cm) with textured bottom, featuring both small and wide riffles. Carbonation was performed in a 1.5 L double-walled Pyrex reactor (16.8 cm height, 10 cm diameter), equipped with high-precision gas flow sensors. CO_2 was bubbled at 0.5 L/min through a porous stone, while an Argo-Lab mixer with a 4 cm helix stirred at 1000 rpm. Conditions were 298 K, 1.2 bar, and a L/S of 10. Solid–liquid characterization included optical microscopy, XRPD with Rietveld refinement, SEM–EDS, Ion chromatography, ICP–MS, and XRF. EN 12457-2 leaching tests were applied to raw and treated material. Key findings demonstrate that pre-carbonation EMR reduces the leachability of the carbonated demetallized IBA, improving the stability of the treated material for potential reuse as additives. Magnetic separation efficiently concentrates Fe, Cr, Ni, Mn, and Co (originating mainly from steel production) while density separation mainly concentrates Cu, Zn, Sn, Ni, Zr, Pb, Sb and Ag. XRF and SEM–EDS results highlight the effectiveness of density separation in isolating Sb, primarily bound in high-density Pb–Sn–Sb oxides such as $Pb(Sn, Sb)O_3$ and $Pb_3(Sn, Sb)_2O_7$. These phases were found in both the UF (< 0.063 mm) and > 0.25 mm sand fractions. The UF fraction (< 0.25 mm) exhibited the highest CO_2 uptake (up to 120 gCO_2/kg IBA), with uptake decreasing as particle size increased. Precious metals were also detected: gold (Au^0) as microparticles (< 10 µm) dispersed throughout the UF fraction, and silver (Ag^0) in both UF and coarser fractions, with Ag^0 particles up to 2 mm in diameter. In conclusion, coupling EMR with ACT for fine IBA treatment in the liquid phase offers a promising route for strategic metal recovery, CO_2 mitigation, and additive production, within a circular economy and CO_2 emission reduction perspective. Future work will address scale-up feasibility, industrial separation technologies (e.g., centrifugation, wet shaking table), metal concentrate refining, water reuse, and the valorization of carbonated end-products.

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S26.

Geological, biological and anthropic constraints on landscape evolution

CONVENERS AND CHAIRPERSONS

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Response of two Ligurian embayed beaches to storm Vaia

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Keywords: embayed beaches, storm, resilience.

Understanding the response of coasts to extreme events is a central step in implementing reliable strategies for integrated coastal zone management, particularly in the context of climate change. Sea level rise (SLR) is one of the most investigated phenomena associated with climate change, and studies indicate that it will exacerbate coastal erosion processes. Approximately 80% of the world's coasts are rocky (Emery & Kuhn., 1982), and among the morphologies associated with this type of coast are embayed beaches, which are one of the most widespread coastal morphologies. This study investigates the effects of an exceptional event that hit the Ligurian coast between 29 and 30 October 2018 on two embayed beaches on the eastern Ligurian Riviera. The storm Vaia inflicted damage to many coastal infrastructures along the entire Ligurian coast: several sections of the coastal road network were disrupted, many harbours sustained damage, and numerous coastal buildings also reported damage (Oprandi et al., 2020). The beaches under investigation show different features in terms of artificialisation; Bonassola beach is free from coastal structures, while Levanto beach features several groynes that divide it into distinct sectors and remains of old submerged structures now destroyed. From the sedimentological point of view, both beaches can be classified as mixed sand-gravel beaches. The study activities were conducted through field surveys and coastal modelling (XBeach model). In detail, topographic surveys were conducted a few days before, immediately after and eight months following the storm impact. Despite significant damage to coastal infrastructures, the obtained results highlight a high level of resilience in response to the storm's impact for both investigated beaches. There was no evidence of structural erosion phenomena, and the beaches' equilibrium remained intact. Bonassola beach, which experienced significant coastline rotation, exhibited the most pronounced effects of the storm impact. However, eight months later, the subaerial portion of the beach was restored. In conclusion, this study illustrates how embayed beaches can withstand even exceptional events without compromising their natural equilibrium.

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SUBSURFICE: a project to improve the knowledge of ice stored inside rock glaciers and related ecohydrological effects

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Keywords: subsurface ice, rock glacier, climate change.

Due to the rapid shrinkage of mountain glaciers, subsurface ice, including ground ice in rock glaciers (RGs), is expected to become a significant groundwater reservoir under future climate warming (Haeberli et al., 2017). However, there are still many open questions about the ice volume stored inside RGs, its spatial distribution and its ecohydrological significance at the regional and global scale.

Recent research highlights that Alpine permafrost occurrence can be widespread in pseudo-relict rock glaciers, i.e. rock glaciers that appear to be relict but contain patchy permafrost (Carturan et al., 2024). This evidence suggests very long response times for subsurface ice contained in RGs, and underlines the need for improved knowledge of this component of the Alpine cryosphere.

By means of an interdisciplinary approach, the SUBSURFICE project combines geomorphological and thermal methods, environmental tracers (stables isotopes of hydrogen and oxygen, electrical conductivity (EC), major ions and trace elements), advanced geophysical methods, and biological techniques to investigate selected study sites in the Eastern Italian Alps, including active, transitional, pseudo-relict and relict RGs.

Comparing RGs with different activity in a wide range of environmental conditions, the project uses a "space-for-time" substitution approach, to account for the possible future decay of intact landforms under atmospheric warming.

The geomorphological, geophysical and ground thermal studies confirm interesting parallelisms between intact and pseudo-relict RGs, with permafrost still existing and affecting the local ground surface and subsurface in RGs at low elevations, even below the local treeline. On the other hand, significant differences exist in RGs located at similar elevations and with the same apparent degree of activity, as assessed from external geomorphological characteristics.

Spring waters downslope of relict and pseudo-relict RGs had lower EC compared to intact RGs. The seasonal isotopic enrichment due to the decreasing snowmelt contribution was more evident at high elevations. Intact RG springs had higher concentrations of sulphates, when compared with relict RGs and springs unrelated to RGs. This difference was more evident at locations with acidic metamorphic lithologies.

At some RG springs, sulphate and trace element concentrations exceeding the standard for drinking water quality suggest potential issues related to the human use of RG water. Even though this issue mostly regards springs from intact RGs, local significant enrichment in ions and trace elements was also identified at some springs fed by relict and pseudo-relict RGs.

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Pedological and geotechnical analyses at soil profile scale to evaluate shallow landslide susceptibility in a pilot catchment of Calabria, (Italy)

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Keywords: shallow landslides, soil properties, triggers factors.

This study investigates the influence of soil properties on slope stability and shallow landslide triggers in the Turbolo Stream catchment, Northern Calabria (Southern Italy). The alteration of the parent material leads to differential changes in their resistance, making them more susceptible to the force of gravity and creating weakness layers where failure surfaces can develop. The catchment, covering approximately 30 km^2, was chosen because of the occurrence of many landslides and geo-environmental features that can be considered similar to those of several Mediterranean catchments. The main soil types range from highly mature soils (Alfisols) to poorly differentiated soils (Inceptisols and Entisols). While previous research in the area addressed landslide susceptibility through geological and geomorphological factor, the role of soil characteristics remained underexplored. The project "SOIL SHADES – SOIL features and pedogenic processes as predisposing factors of SHAllow landsliDES", funded by Next Generation EU, National Recovery and Resilience Plan (PNRR) of Italy, M4.C2.1.1., National Research Programme (PNR)–Research Projects of Significant National Interest (PRIN), aims to fill this gap and brings together numerous direct and indirect methodologies, trying to address this research question. Six representative soil profiles, developed on both crystalline Paleozoic-Cretaceous rocks and Neogene deposits, were analyzed. Proximal and remote sensing techniques were coupled with field description. For all profiles, individual horizons were sampled, and both pedological (chemical and physical) and geotechnical analyses were performed. In addition, the observation of soil thin sections under a polarizing optical microscope enabled to detect soil micromorphological features, especially those that may affect the physical properties of the horizons (porosity, clay coatings etc.). Despite heterogeneous behavior across and within profiles, some trends emerged. Electrical conductivity (EC) and sodium absorption ratio (SAR), were used to evaluate clay dispersivity following Rengasamy's classification. Three profiles showed dispersive tendencies, suggesting that while dispersivity may play a role, it is not the primary landslide trigger. Trends in shear strength, liquidity limit (WL), plasticity (WP) and plasticity index (IP), together with specific gravity and bulk density, indicate how the parent material, degree of pedogenesis and inherent spatial variability of the soil affect the geomechanical parameters to varying degrees. The final goal of this work is to develop a standardized protocol applicable to any area prone to shallow landslides, offering an effective methodology for risk prevention and mitigation. Consistent with this, the collected data will feed into a predictive model, in order to identify threshold parameters for landslide initiation.

Integrated assessment of erosion rates in the Sfalassà catchment (Calabria, southern Italy) using cosmogenic nuclides and a semi-quantitative erosion model

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Keywords: cosmogenic ^{10}Be, erosion modelling.

Understanding the evolution of Earth's surface requires integrative approaches to quantify erosion and sediment transport across spatial and temporal scales. This study investigates sediment dynamics in the Sfalassà catchment, a geomorphologically and lithologically heterogeneous basin in the central Mediterranean (Calabria, southern Italy). We combine in-situ cosmogenic ^{10}Be analyses with a modified Erosion Potential Model (EPM) to estimate long-term erosion rates, sediment residence times, and annual sediment production across the catchment. While the ^{10}Be data provide direct insights into erosion on millennial timescales, the EPM offers an indirect, spatially distributed estimate of sediment yield on an annual basis.

A total of 20 samples, including river sands of varying grain sizes, were collected along the main stream and its tributaries. Field campaigns were supported by remote sensing, GIS analysis, and thematic mapping to characterize surface conditions and guide site selection. The EPM was upgraded by integrating geological and pedological erodibility factors, refining lithological classes, and extrapolating rainfall data through elevation-based regressions. Soil erodibility parameters were calibrated based on bulk density measurements of topsoil samples collected from 27 sites across the catchment.

The integration of cosmogenic nuclide data and empirical modelling provides a robust framework for understanding sediment connectivity and fluxes from source to sink, supporting sediment budget assessments and risk management in coastal areas. This work, part of the TECH4YOU project (PNRR M4.C2.1.5), contributes to the development of reproducible methods for geo-environmental analysis in complex Mediterranean landscapes.

PFAS contamination in deep groundwater: the case of Parma, Northern Italy

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Keywords: groundwater, PFAS, emerging contaminants.

Per and PolyFluoroAlkyl Substances (PFAS) are a wide class of of synthetically made chemicals, characterized by the presence of carbon fluorine bonds. This chemical structure gives them stability, which makes them attractive for use in numerous industrial products (Gaines, 2023). However, the same properties that justify their wide industrial use, are also the basis of their high environmental persistence and bioaccumulability. Also known as "forever chemicals" (Diaz & Stewart, 2019), some PFAS are associated with toxicological effects relevant to human health, including endocrine interference, liver dysfunction, increased risk of certain malignancies and possible effects on fetal and infant development (Panieri et al., 2022). Since 2010, with the European Commission restrictions on the use long-chain PFAS (such as PFOA and PFOS), there has been a transition to the use of short-chain compounds, such as PFBA, PFHxA and PFHpA. Although initially considered less persistent and toxic, the remarkable chemical stability and environmental persistence of short-chain PFAS, often comparable to or superior to that of long-chain PFAS, has been proven (Li et al., 2020). For these reasons, PFAS are classified as emerging contaminants and are a growing priority in environmental and health research.

In the present work, a multidisciplinary investigation has been carried out in the context of the multilayer alluvial aquifer of the Parma plain, integrating: (i) hydrogeological investigations; (ii) tritium (^3H) analysis, used as an environmental isotopic tracer, carried out to estimate the average groundwater residence times at each sampling point; (iii) chemical analysis of both short-chain and long-chain PFAS; (iv) characterization of the microbial community, in order to verify potential natural attenuation phenomena.

The monitoring included sampling of wells screened at different depths. Chemical analyses showed the presence of PFAs, however, not all groundwater monitoring points exhibited instrumentally detectable PFAs concentrations, suggesting a heterogeneous distribution of the chemical compounds within the complex aquifer system. The conceptual hydrogeological model was therefore reconstructed in detail, as to identify the hydraulic interconnections between the more permeable horizons coexisting within the heterogeneous system, and between these horizons, the streams and the ground surface. The analysis of potential migration paths of PFAS at the basin scale, combined with the study of microbial communities naturally present in the groundwater, has raised questions about the influence of well characteristics and management practices on the distribution of contaminants in surface and deep water.

The findings highlight the complexity of the processes that regulate the fate of emerging contaminants in the hydrosphere and underscore the importance of multidisciplinary approaches for the understanding and sustainable management of water resources in environmental contexts under increasing anthropogenic pressures.

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Geomorphological landscape evolution under anthropic impact in a small but highly urbanized catchment in Genoa (Italy)

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Keywords: urban geomorphology, anthropic landforms, natural hazards.

The geomorphological landscape in urban environments is characterized by modified natural and anthropic landforms, often related to urban phases developed over time, even through centuries. The comprehension of geomorphology in the urban environment is therefore complicated by the human-made fabric covering natural landforms and requires a multidisciplinary approach with contributions from the disciplines of city planning and historical geography.

In the Mediterranean area, the most ancient anthropogenic modifications of natural landscapes probably date back to protohistoric times, but the most significant are related to the period of the industrial revolution, and have continued through various boosts in the 20th and 21st centuries.

Genoa is a city of about 600,000 inhabitants and one of Italy's economic and product centres, as well as an important university, scientific, cultural and tourist hub. The port of Genoa is the largest nationwide and one of the most important in the Mediterranean area.

Although the oldest settlement in Genoa dates back to the Neolithic period, it was in the Middle Ages that the city established itself as a maritime republic, with its characteristic historical centre, and kept a practically constant structure until the 19th century.

The large-scale urban planning operations carried out from the first half of the 19th century partly changed the original physical setting of both the historic centre and the outer areas. It is the case for many small catchments which are now included within the city area, whose geomorphological dynamics have been completely altered by the rapid spread of urbanisation.

This research presents the preliminary results coming from the analysis of the morphological changes occurred over the last 100 years in the Rovare stream catchment (approximately 2.5 km2), which is located in the Eastern part of Genoa within the lower part of the Bisagno stream catchment. The upper Rovare catchment hosts the San Martino hospital and one of Genoa's five university campus. In the final stretch, the stream flows alongside the culvert of the better-known Bisagno stream.

The anthropic impact first occurred at the beginning of the 20th century with the construction of hospital pavilions, which resulted in major changes to the ground surface, both by cuts and fills, and then from the 1950s onwards with intensive construction of residential buildings.

In addition to ground surface changes, which are recognisable through multi-temporal cartographic comparisons and analysis of stratigraphic logs, artificial cavities have been recognised, such as culverted riverbeds, air-raid shelters, and service tunnels for hospitals.

The documented landscape changes appear to have promoted geo-hydrological hazards, also in the light of climate change: in recent times there have been processes such as sink-hole phenomena, flooding and hydraulic stresses related to the culvert of the Rovare hydrographic network.

Geomorphological evolution of a Mediterranean coastal area subject to fast urbanisation

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Keywords: urbanisation, geomorphological evolution, ground classification.

When dealing with geomorphological studies in the urban environment, among the main issues are the reconstruction of the original geomorphological context, with the consequent recognition of all the modifications that have occurred, and the quantification of the geomorphic impact of urbanisation.

In the Mediterranean region, many of the major cities have undergone a very long history, starting in the Middle Ages or even earlier. Because of this, they often exhibit a complex and stratified geomorphological evolution. The city of La Spezia, located on a small coastal-alluvial plain in eastern Liguria (Italy), is a particular case, as its urbanization was very rapid and linked to a single historical event. The construction of a military port at the end of the 19th century, and the following economic growth, led to the transformation of a small hamlet into a city of 100,000 inhabitants in just a few decades. La Spezia is therefore a laboratory for the recognition of the geomorphologic imprint linked to rapid urbanization of a territory.

The recent geomorphological evolution of the city of La Spezia has been studied through the analysis of three historical stages: i) the phase prior to the construction of the military port, referring to the first half of the 19th century; ii) the phase immediately following the construction of the military port, referring to the end of the 19th century; iii) the current situation. The geomorphological context of the three stages has been reconstructed through the analysis of historical and recent maps, paintings, technical documents, bibliography and aerial imagery. For each of these three stages, a simplified geomorphological sketch was produced, using a ground classification modified after Rosenbaum (2003).

The results of this research show how the rapid growth of the city has led to a complete upheaval of the local geomorphological context: most of the original natural landforms have been erased, while new landforms have appeared due to excavations and embankments; furthermore, the hydrographical network has been heavily modified, and is now mostly culverted or channelized.

The proposed methodology is useful for reconstructing the geomorphological context of past stages that have now been completely modified, and allows to obtain quantitative results regarding the anthropogenic geomorphic imprint. Furthermore, it can be easily replicated in other similar contexts. The results of the research also provide tools for mitigating geomorphological risk in urban environments, and represent useful knowledge for raising awareness of the geomorphological impacts of rapid urbanization.

Unveiling the long-term landscape evolution of the Transantarctic Mountains

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Keywords: thermochronology, surface processes, Antarctica.

The long-term landscape and tectonic evolution of the Transantarctic Mountains reflects the interplay resulting from surface processes and deep processes, where efficient erosion of the uplifted rift shoulder contrasts with mechanisms sustaining a remarkably high topography. Numerous hypotheses have been proposed to explain the topographic structure of one of the largest and highest rift shoulder on the planet, which formed at the western boundary of the West Antarctic Rift System. Since the Cretaceous, the geological evolution of the Transantarctic front has been punctuated by extensional tectonics, magmatism and climate-driven events, including the onset of ice sheets whose variability heavily reshaped the rift shoulder.

In this contribution we present an updated morphometric analysis of both exposed and subglacial topography, along with a preliminary analysis of available published apatite thermochronological data, integrated with minimum exposure ages and field-based geomorphological constraints.

The morphology of the Transantarctic margin is marked by outstanding erosional and fault-related escarpments intersected by transverse troughs. These valleys developed through a combination of surface processes, including different erosion styles such as fluvial, fluvio-glacial, warm-based glacialism, and cold-based glacialism. High-resolution surface digital elevation models highlight the influence of orthogonal to oblique rift-related faulting on the morphotectonic evolution of the Transantarctic Mountains. Meanwhile, low-resolution bedrock digital elevation models allow to investigate morphological patterns using topographic metrics, hypsometric distribution and swath profiles. Contrasting elevation distributions reflect the spatial heterogeneity of interactions between glacially-driven surface processes, mantle thermal anomalies and rock uplift. In addition, thermochronological data interpreted at a broader scale along longitudinal and transversal transects of the Transantarctic front may define exhumation patterns. Preliminary analysis of exhumation rates derived from apatite thermochronology modeled using additional constraints for post Miocene erosion, investigate how different sectors of the Transantarctic Mountains responded to Cenozoic climatic and tectonic history.

Potential of Google Earth Engine and supervised classification for rock glacier mapping: a case study from the Southwestern Alps

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Keywords: rock glaciers, Google Earth Engine (GEE), machine learning classification, permafrost monitoring.

Rock glaciers (RGs) are vital landforms in alpine environments that serve as indicators of permafrost presence and function as natural water reservoirs. Their role in long-term water storage is particularly crucial because climate change accelerates glacial retreat and permafrost degradation in high mountain regions. Currently, many RG datasets are created using traditional mapping methods, which are manual, time-consuming, and limited in spatial scalability. Utilizing cloud-based machine learning within the Google Earth Engine (GEE), this study presents an automated approach for identifying RGs in the Southwestern Maritime Alps. Input Environmental predictors such as topographic and spectral indices, land surface temperature (LST), and surface properties were calculated using a digital elevation model and multiple satellite datasets (Optical and Radar). The supervised algorithms, Random Forest (RF) and Classification and Regression Tree (CART), were trained using valid inventory data from RGs obtained through manual digitization and field surveys. A K-fold cross-validation method was employed to prevent overfitting and to ensure model robustness. Among the classifiers, RF demonstrated the best validation results, achieving an accuracy of more than 85% and high precision, recall, and F1-score, along with an R2 of 0.81 across all folds. Feature importance analysis revealed that elevation, Topographic Position Index (TPI), LST, and SAR-based coherence were the top environmental predictors in the RF classification model. These characteristics enable the differentiation of rock glaciers from similar landforms. The significance of elevation and TPI reflects a periglacial setting, whereas SAR coherence maps illustrate surface movement or stability, allowing for the distinction between non-moving debris sites. Incorporating land surface temperature reinforced the model's sensitivity to permafrost as it responds to ground temperature changes. Through morphological filtering, smoothing, edge detection, area filtering and applying an elevation-slope threshold, 297 RGs were identified following post-classification processing. The method presented in this study can be adopted and tested in other alpine regions as well as on a broad scale to improve the monitoring of permafrost landforms under climate change. The inclusion of InSAR time series and deep learning methods is suggested for the future detection of RGs.

Interaction between different rainfall and magma injection rates to control volumes and topographic uplift: insights from analogue modelling

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Keywords: magmatism, rainfall, analogue modelling.

Magmatism plays a crucial role in driving topographic changes and understanding how topography responds to deep magmatic intrusions is a key frontier in geothermal resource exploration. In this study, we present a series of analogue experiments designed to explore the influence of magma injection rate and rainfall intensity on the evolution of magmatic doming of the pre-existing surface. While analogue models have already provided significant insights, revealing that topography forms a dome-like shape above the magma feeder, these models have not considered the role of surface processes. The contribution of climate, specifically rainfall, in shaping the final landscape during shallow magma intrusion remains unexplored.

We tested how magmatic dome growth and morphology is affected by three different rainfall rates (680, 920, and 2700 $mm^3 h^{-1}$) and three different magma injection rates (5.8, 16, and 60 $mm^3 h^{-1}$). By systematically varying these parameters, we identified key controls on the geometry of the domes, based on volumes of surface uplift and topographic height at different time steps during the experiments.

Overall, our results highlight the sensitivity of uplift and topographic peak formation to specific ratios between magma injection and rainfall rates. We observed that high rainfall intensities are more effective in shaping the landscape when coupled with a specific magma injection rate, and vice versa. Notably, higher volumes of uplift were observed at increasing rainfall rates, likely as a response to the redistribution of overburden with consequence unloading, which facilitates the upward push of the injected magma, enhancing uplift beyond initial expectations. In contrast, topographic peaks were sensitive to rainfall rates only at higher magma injection rates, indicating that high rainfall alone does not control peak height.

Geomorphological mapping of the mountain area of Friuli Venezia Giulia Region: the CGT project

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Keywords: geomorphological mapping, landslides, GIS.

The Department of Mathematics, Informatics and Geosciences of the University of Trieste (MIGe) has a research agreement with the Geological survey of the Autonomous Region Friuli Venezia Giulia (SGEO RAFVG) for the continuation of the geological-technical map project (CGT). This work aims to create thematic maps and an informatic database about the geological-technical features of the Friuli Venezia Giulia Region (FVG).

The goal of this project is the production of a geomorphological map and a gravitational instabilities map (GIM) of the mountainous sector of FVG (Julian and Carnic Alps and Prealps, extending to the foothills and the moraine hills of the Upper Plain), covering an area of over 4.000 km^2.

The development of the above-mentioned maps is carried out integrating bibliographic data, satellite imagery, high-resolution digital terrain models (DTMs), and validated by means of field observations. Particularly effective is the interpretation of high-resolution images and DTMs, along with their derived products, available for the entire regional territory at a resolution of 0.5 m. All information is digitalized and stored in a GIS environment.

The geomorphological map depicts landforms and deposits associated with the processes of landscape evolution and shaping, with particular attention given to anthropogenic features. Among these, special emphasis is placed on riverbank and slope mitigation works. Data from the Informative System for Soil Defense (*Sistema Informativo per la Difesa del Suolo*, SIDS) are integrated with direct field observations, to verify and update the current conditions of the structures. The map legend is structured according to the main morphogenetic processes — fluvial, glacial and periglacial, karstic, litho-structural, tectonic, and anthropogenic — that characterize the landscape of the south-eastern sector of the Alps.

GIM includes updated representations of gravitational instabilities, based on the data initially catalogued by the SGEO RAFVG for the landslide inventory, and prepared according to the standards of the IFFI Project (*Inventario dei Fenomeni Franosi in Italia*, Italian Inventory of Landslides). Within the same thematic framework, subsidence sinkhole phenomena are included. Data regarding them are derived from a regional inventory, which is currently updating as part of another ongoing research agreement between SGEO RAFVG and MIGe.

The ultimate goal of the project is to provide an updatable GIS, including the production of a regional map at a scale of 1:150,000, in which geomorphological analysis serves as a well-established method for identifying the landscape evolution processes occurring on the Earth's surface. These tools are essential for conscious land-use planning and for the investigation of geological hazards.

Surface water concentration on active landslide portions in the Northern Apennines (Italy), integrating GIS-based analysis and field data

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Keywords: landslide, water body, Northern Apennines.

The availability of fresh water bodies is crucial, and it could be more in the future, for those territories that particularly will suffer for the climatic changes. In relation to the increasing atmospheric warming and the northern shift of arid and semiarid environments, the mountain chains of the mid latitudes in the Mediterranean area could be potentially interested by a reduction of fresh waters availability. Thus, it is important to analyse the natural vocation to the water concentration of land surface and subsurface in relationship with the geological and geomorphological features.

The distribution of small water bodies associated to landslides in the western part of the Northern Apennines (Italy) has been explored, for the first time, using GIS analysis, field surveys and geophysical imaging. The analysis of surface soil moisture patterns based on topographic characteristics in the whole investigated area was performed using the Topographic Wetness Index (TWI). The case studies correspond to two large landslides deep-rooted in the bedrock. The Sauna landslide in the Parma torrent basin and the Berceto landslide in the Taro river basin, have been investigated through field work, geophysics, boreholes and radiocarbon dating for the time constraints of the water bodies. The TWI analysis carried out both at the regional and the case-study scale has shown that low values of this index (drier areas) are more associated with inactive landslide portions, whereas higher values (wetter areas) are more associated with active landslide portions. As highlighted by geophysics, these landforms are in connection with deep shapes of the sliding/rupture surface of the landslide that mimic those at the surface. The analyses on the case studies highlighted that the condition characterized by wet soil and/or the presence of small water bodies are spatially persistent across time in correspondence of the same portion of the landslide that preserves landforms able to maintain these waters.

The dating of the deposits related to the water bodies allowed to focus on dynamics occurring on timescales spanning from secular to millennial.

In situ characterization of snow dielectric properties from 100 MHz to 2 GHz

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Keywords: cryosphere, snow dielectric properties, in-situ measurements.

Snow cover is the most extensive component of the cryosphere, influencing various Earth system processes, from radiative balance to climate, glacier mass balance and water resources. Monitoring the physical and dielectric properties of snow is essential to improve the understanding of snowpack dynamics, hydrological processes, and their climate interactions. Dielectric characterization is particularly important for remote sensing. In-situ measurements are key to improve the interpretation and validation of satellite observations, with implications for water cycle studies, resource management, and avalanche monitoring. Several models describe snow dielectric properties and their relation to density and liquid water content (LWC), but significant discrepancies persist. While all agree that permittivity increases with LWC, absolute values vary across models depending on density, LWC, and frequency. Likely causes include: i) lack of consensus on water inclusion shapes in mixing models; ii) limited field data spanning all snow and frequency conditions. As a result, model selection is often based on practicality rather than validation, highlighting the need for comprehensive datasets to support or refine existing models.

This study introduces a new measurement protocol using three-wire probes connected to a Vector Network Analyzer (VNA). By analyzing signal resonances, accurate estimates of real and imaginary permittivity can be obtained in the 100 MHz – 2 GHz range. The protocol was applied during two field campaigns in spring 2024 in Val Senales (Italian Alps), supported by "PNRR-M4C2-I1.1-PRIN 2022-PE10-SnowMed - Apennine snow cover in the Mediterranean climate region: multi- sensor data, observations, modeling and trend analysis-F53D2300228 0001-Finanziato dall'U.E. – NextGenerationEU" and conducted in collaboration with EURAC (Bolzano). Over 100 measurements were performed, yielding more than 300 permittivity values using probes of varying lengths (50, 100, 200 mm). A key innovation is the simultaneous acquisition of snow density and LWC via melting calorimetry, enabling direct comparison between physical and dielectric properties. Measurements were conducted throughout the day, allowing analysis of temporal snowpack evolution and capturing LWC values ranging from ~2% to > 10%.

Preliminary results show strong correlation between permittivity and LWC. However, applying different retrieval schemes based on distinct semi-empirical mixing models leads to varying outcomes, especially at frequencies other than 1 GHz and at intermediate LWC values. The portability, speed, and in-situ calibration capabilities of this method support its use in diverse environments, including remote locations.

Future developments will expand the protocol to a broader range of snow conditions and integrate it with other electromagnetic techniques, such as ground-penetrating radar (GPR), for multi-scale snow characterization.

Assessing neotectonic activity in the Solani Basin, NW Himalaya: a geomorphometric–InSAR–GPR approach

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Keywords: active tectonics, ground penetrating radar, differential interferometry.

The Solani Basin, situated in the northwestern Himalaya, represents a tectonically sensitive region shaped by ongoing crustal deformation associated with the Himalayan orogeny. This study evaluates active tectonic processes in the basin through an integrated framework comprising geomorphometric analysis, spaceborne Synthetic Aperture Radar Interferometry (InSAR), and ground-based geophysical investigations. A suite of geomorphic indices—including drainage basin spatial asymmetry, channel gradient, transverse topographic symmetry, and mountain front sinuosity (Nath et al., 2019; Mahesh et al., 2015; Kirby & Whipple, 2012)—was employed to assess spatial patterns of relative tectonic activity. In instances of index disagreement, a weighted synthesis approach was used to derive a composite tectonic activity score, further validated by the presence of drainage anomalies and previously mapped faults and fractures.

To capture ongoing crustal movements, multi-temporal Sentinel-1A SAR data were processed using Differential InSAR (DInSAR) techniques (Hensley & Farr, 2013). The interferometric analysis revealed spatially coherent deformation signals—characterized by subtle uplift and subsidence—closely associated with geomorphically active zones, particularly within the piedmont and transitional fluvial zones. These deformation patterns supported the delineation of tectonically active blocks and validated the morphometric inferences.

Ground-truthing was carried out using bi-static, multi-frequency Ground Penetrating Radar (GPR) surveys in select areas, including Biharigarh and Mujahidpur villages (Uttarakhand and western Uttar Pradesh). High-resolution radargrams from 40 MHz and 100 MHz antennas revealed offset, warped, and discontinuous sedimentary layers, indicating shallow faulting and neotectonic deformation (Nath et al., 2019). These findings directly confirm the presence of active subsurface structures previously inferred from remote sensing and geomorphic analysis.

Finally, the spatial distribution of historical seismicity (Mw > 2.5) was used to validate the interpreted tectonic activity zones. Earthquake clusters exhibit a strong spatial correlation with regions of geomorphic anomalies, InSAR-detected deformation, and GPR-identified structural disturbances, reinforcing the multi-source evidence of ongoing tectonic reactivation.

This study demonstrates the strength of an interdisciplinary approach combining geomorphometry, InSAR, and near-surface geophysics in evaluating tectonic activity in foreland basins. The framework provides valuable insights into the interaction between surface processes and deeper crustal dynamics, with significant implications for regional seismic hazard assessment and geodynamic understanding. The methodology is transferable to other tectonically active terrains globally, aiding in the identification and monitoring of deformation-prone zones.

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Structural Map of seas surrounding Italy

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Keywords: tectonic, structural data, Italian seas.

The Geological Survey of Italy – ISPRA coordinates cooperation among marine geology researchers from different Italian universities and research institutes, in the frame of the European Marine Observation and Data Network (EMODnet) Project Lot Geology.

The objective of the cooperation is to provide products for the "Geological events and probabilities" work package of the Project which includes earthquakes, volcanoes, landslides, fluid emissions and Quaternary tectonics layers. Data gathered so far allowed to realize an update concerning submerged areas of the Structural model of Italy. The map, at the scale 1:1,250,000, aims to present in a synthetic but exhaustive way the structural setting of seas surrounding Italy, a key region in the geologically very active Mediterranean Sea which is dominated by the geodynamic processes of convergence and collision between the European and African plates.

The geological expression of the seafloor surrounding the Italian region is evidenced by structural data from original surveys as well as from scientific literature or derived from national strategic research programmes, properly integrated and validated to create a harmonized dataset.

Features included in the map, represented on top of the EMODnet Bathymetry DTM (http://www.emodnet-bathymetry.eu/), are tectonic elements (faults, folds axes, high-deformation crustal zones), earthquakes, submerged volcanic structures and rocky outcrops, main onshore tectonic elements and volcanic deposits. Moreover, complementary information related to the thickness of the Plio-Quaternary succession, depth of the Moho discontinuity and heat flow are shown as inset maps.

This map highlights the current geological-structural setting of seas surrounding Italy and emphasizes the features that have contributed mostly to the present conformation of the Italian seafloor and, among them, those that may originate geohazards.

The map can be considered as a solid base for more detailed studies of seismotectonics and applied geology, for territorial management and spatial planning as well as for scientific dissemination.

European Commission, Directorate-General for Maritime Affairs and Fisheries, 'EMODnet Digital Bathymetry (DTM)', 2018, accessed 2025-05-12, http://data.europa.eu/88u/dataset/EMODnet_bathymetry.

How reliable is inferring tidal elevations of coastal features from biological zonation bands?

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Keywords: biological zonation, tidal datum, Livorno (NW Italy.

Assessing the elevation of features in coastal areas is crucial for practical measurements e.g. in coastal engineering activities or in sea-level change determinations. Elevation of a point in a specific area is stated relative to a vertical "datum". Tidal datums (e.g mean sea level) are defined with reference to the sea surface and are calculated by averaging tidal phases or hourly mareographic records over specified timespans. Along coastal areas, where elevations should be assessed with the most accurate adherence to the actual position of sea surface, the tidal datum is the most suitable reference system. As such, a tidal datum has a local validity within a limited but undefined area and may be modified by ongoing sea level rise. For practical purposes referencing techniques based on the arrangement of biological assemblages along a rocky shore into elevation bands (biological zonation) have been adopted. These techniques are based on the assumption that there is a fixed spatial relationship between the position of biological assemblages along a rocky shore and tidal elevations. The original formulation of the concept of biological zonation, however, has been widely revisited by ecologists, by incorporating the role of variability in biological interactions and additional physical factors in shaping the spatial (both horizontal and vertical) and temporal distribution of organisms in intertidal habitats. In this work preliminary tests carried out along the rocky shore of Calafuria (Livorno, NW Italy) are illustrated. In the study area, the vertical distribution of the main sessile organisms is typically characterized, from lowshore to highshore, by a band of brown algae (*Cystoseira sensu lato*), followed by a band of red coralline algae (e.g. *Lithophyllum* spp.), whose upper boundary coincides with the lower limit of areas dominated by barnacles (*Chtamalus* spp.). The vertical distribution of benthic organisms was measured with reference to the tidal elevations assessed through the recordings of the Livorno tide gauge included in the Italian National Tide Gauge Network. The overall width of the biozonation bands shows significant variability even on a limited spatial scale (a few km). Furthermore, the boundary between the *Cystoseira* band (lower) and the coralline algae band (upper), potentially corresponding to mean low water of neap tides (MLWN) shows a wide elevation range up to approx. 60 cm. Results suggest that the relationship between biological zones and tidal levels is not univocally determined as previously assumed, not even at relatively small scale. In spite of the general validity of the traditional concept, the methodology should be adapted based on site-specific surveys aimed at testing the local response of biological assemblages to local changes of biological and physical factors.

Impact of debris flows on soils in the surrounding of Alpe di Succiso Mt., Northern Apennines (Italy) and the contribution of geopedology in the characterization of past events

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Keywords: soils, debris flow, Appennines.

In active landscapes such as mountainous environments, soil evolution is primarily influenced by topography. Slope dynamics and instability play a key role in soil formation, development, and preservation. As a result, soils serve as valuable archive for reconstructing past environmental conditions and provide insight into the morphodynamic processes that have influenced the landscape over time.

To fully understand the interplay between surface processes, vegetation, soil development, and water circulation, a multidisciplinary approach is essential. For this reason, a scientific research project was started on the north-facing slope of Alpe di Succiso Mt. (DECC, 2023), with the primary objective of assessing the spatial and temporal distribution of debris flow events and to develop models for their occurrence. The project uses a multidisciplinary approach, involving the integration of geomorphology, dendrochronology, hydrological monitoring, climatology, and geopedology.

In the framework of the DECC project, the geopedological research focuses on characterizing the soils within two distinct toposequences: one situated along a stable slope, and the other along a slope affected by debris flows. Eight soil profiles were analyzed using a suite of methods, including routine soil analyses (grain-size distribution, total organic carbon, pH, and Fe/Al extractions) and micromorphological investigations.

Particular attention was paid to the information recorded in the soils in order to understand how geomorphological context and recent rainfall events contribute to the formation and evolution of these toposequences.

The main results show that all profiles exhibited limited thickness and a low degree of development. However, soils on the stable slope appeared to be relatively more evolved. An increase in the sand fraction was noted in profiles located on the debris flow-affected slope. The profile with the highest sand content was found in the debris flow deposition zone, near an area where trees showed clear signs of disturbance, despite the absence of visible debris flow deposits on the surface. The higher sand content in this profile suggests the accumulation of coarse material from upslope during one or more debris flow events that occurred in the area.

In the context of ongoing climate change and increasingly intense precipitation events, the integration of geopedological results with findings from other disciplines allows a more accurate reconstruction of environmental changes and slope dynamics. A multidisciplinary approach contributes to the assessment of local hazards and supports the development of safety measures aimed at protecting both the natural environment and the people who visit the Alpe di Succiso area.

DECC (2023) – DECC: Debris flow hazard and climate change in the Northern Apennines: reconstructing and modelling past and future environmental scenarios. PRIN 2022 PNRR - Projects of Great National Interest, Financed by the European Union – Next Generation EU.

Understanding historical hydrocarbon release in urban alluvial aquifers: could be 3D contaminant spatialization a key tool to guess the pollution dynamics over time?

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Keywords: groundwater, contamination, hydrocarbon release.

The environmental impact resulting from leaking underground oil tanks poses a serious threat to ecosystems due to the migration of contaminants into the surrounding soil and groundwater. Understanding the dynamics of such pollution events is essential to support effective remediation strategies. This study employs a multidisciplinary methodology to reconstruct contaminant migration over space and time, starting from hydrogeological conceptual modeling. The investigation was conducted on a decametric-scale test area located in the alluvial aquifer of the Parma plain, focusing on the first 20 meters of the subsurface. This area is known to have been potentially impacted by hydrocarbon leakage from an underground storage tank several decades ago. Subsurface data were collected through core drilling, with stratigraphic descriptions used to build the 3D geological model. Sediment samples were analyzed to determine the concentration and distribution of contaminant. Additionally, four piezometers were installed on-site to monitor the groundwater system both quantitatively and qualitatively, enabling the collection of water samples for chemical and tracer (microorganisms and isotope) analysis in addition to the assessment of piezometric levels. Initial spatial distribution of the oil contamination was based on sediment sampling results, which were subsequently used to model the three-dimensional distribution of the concentration plume. The resulting 3D reconstruction of the oil plume revealed a morphology not fully consistent with the current hydrogeological conditions of the aquifer. Specifically, the plume was found to be largely located in the actual unsaturated zone, and its maximum spread occurred well above the saturated-unsaturated interface as might be expected. These features indicate that the contamination event occurred under hydrogeological conditions different from those currently observed, likely when the groundwater table was significantly closer to the surface. The study underscores the dynamic character of subsurface contamination processes and demonstrates how changes in the groundwater system over time can significantly affect the distribution of pollutants. It highlights the importance of integrating temporal and spatial variations into hydrogeological models to improve the design and effectiveness of remediation efforts.

Dynamics and deposits of hydrothermal eruptions

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Keywords: hydrothermal eruptions, volcanic deposits, volcanoes as landscape modeler.

Hydrothermal eruptions (HEs) are driven by the expansion of hydrothermal fluids against atmospheric pressure, without the involvement of fresh magma (Barberi et al., 1992). They should not be confused with the steam blast often occurring as initial event of magmatic eruptions. Some recent HEs were described, such as those that occurred in 1871-1873 at Nisyros, which were reported by the French mineralogist Henri-Claude Gorceix (Marini et al., 1993).

Today, there is still a lack of clarity on several aspects of HEs, such as their mechanisms and deposits. To understand the dynamics of HEs, it is necessary to recall that pressure distribution in boiling hydrothermal aquifers brings them close to becoming mechanically unstable concerning their confining burden. Consequently, a decrease in the external pressure or an increase in the internal pressure or an earthquake can trigger a HEs, without any need to invoke magma uprise at shallow levels.

Based on our observations of HEs deposits in different sites – Nisyros, Milos, Solfatara, Larderello, El Hierro, Montserrat, and Agua Shuca – as well as on historical data, the dynamics of HEs comprises an initial blast, which is largely responsible for cratering and opening of the conduit, and a subsequent open-conduit eruptive stage, with the emission of fluids drained from the hydrothermal aquifer. Accordingly, the HEs deposits are made up of fragments of pre-existing rocks, mostly affected by hydrothermal alteration, with a distinct fragmentation degree. The initial-blast deposit is represented by a fine ash fallout, whereas the open-conduit deposit varies from mudflow to debris flow as a function of the blocks/matrix ratio.

Soon after the end of the HE, the solid particles of the deposits are soaked in the hydrothermal liquid. Given enough time, water-rock interaction and evaporation of the hydrothermal liquid cause the production of several authigenic solid phases such as gypsum, anhydrite, alunogen, alunite, jarosite, alum-K, halite, and goethite. Indeed, the presence of goethite on the surface of the debris-flow blocks is a key feature of HE deposits, even if weathering can cause the removal of the finer fractions of the deposits and the dissolution of highly soluble authigenic minerals.

Last but not least, HEs are heralded by a few precursors occurring very shortly before the beginning of the event. Thus, despite the limited distribution of their deposits, HEs pose a serious risk that must be properly considered.

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Geological map of the Pleistocene volcano of Monte Amiata (Southern Tuscany, Italy)

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Keywords: Monte Amiata, geological mapping, UBSU.

Monte Amiata (305–231 ka; Italy) is an uncommon example of an entirely effusive silicic (mainly trachytic) composite volcano. A detailed geological map (1:25,000 scale) based on Unconformity Bounded Stratigraphic Unit criteria is presented, accompanied by volcano-tectonic, stratigraphic relationship, and volcano evolution schemes. The volcanic facies analysis and structural analysis criteria have been applied to decipher Monte Amiata's geological evolution and structure, and to infer the relations between volcanism and regional tectonics. Based on the occurrence of a first-order geological unconformity representing a paleo-weathering surface of paleoclimatic significance, two major volcanic stratigraphic units and seven phases of activity are recognized.

Unlocking hidden water reservoirs through Ground-Penetrating Radar detection of permafrost ice in alpine rock glaciers of the Southwestern Alps

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Keywords: permafrost, GPR, water reservoir.

Rock glaciers which are the melange of ice and debris are one of the most important but largely understudied water reservoirs in high mountain regions. Their capacity to accumulate frozen water for long time has become more important as the traditional glaciers decrease due to continuous climate-warming. This research is the outcome of GPR investigation implemented on the Vej Del Buoc rock glacier in the southwestern Alps. The purpose was to determine the internal structure of the glacier, find out the thickness of the ice-rich permafrost layer, and estimate the amount of stored water. 25 MHz unshielded antenna was used to collect GPR profiles at various transects across the accumulation zone and frontal lobe of the glacier. The chosen antenna frequency achieved significant levels of penetration into the depth, which was vital in the determination of internal ice layers despite the rough debris on the surface. Data processing involved filtering, gain adjustments and deconvolution techniques in order to improve reflector clarity. Some of the important subsurface layers identified include the seasonal snow cover, the thawed active layer, top of the ice-rich permafrost and a bottom basal reflector, which corresponds to the bedrock. The results revealed that active layer varies from 2.7 to 3.0 m, whereas ice rich permafrost layer is averagely 20 m in depth in the average of all the zones of rock glacier. Quite unique reflections in this layer indicate the presence of huge ice lenses that may be fragments of older glacial ice. The cryological interpretation was confirmed by the tomographic electrical resistivity (ERT) data collected along the GPR survey lines. The estimated mean thickness of rock glacier yielded an assumption of 50% ice content; thus, the total water equivalent storage volume was determined as about 5.83×10^5 cubic meters. This work is the first to quantify rock glacier water storage in a field setting within the southwestern Alps, emphasizing their role in buffering climate impacts to hydrology. The results highlight the importance of GPR in the study of cryosphere and indicate that, among future assessments of water resources, rock glaciers should be considered for inclusion in such regions where snow and ice reserves depict a downward trend.

Fault-related folding on Mercury: Transverse isotropy and the importance of layering in Mercury's upper crust

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Keywords: thrust belts, fault mechanics, Mercury.

Thrust faults are known to accommodate shortening by inducing folding (e.g. fault–bend, fault–propagation, and faulted detachment folds) in some situations. However, the role of anisotropy, specifically the transverse isotropy (i.e. layering/bedding), is an underappreciated parameter in the ability to producing folds from faulting. On Mercury, global contraction produced a variety of thrust fault scarps, some of which may have compensated the contraction by producing folds (Loveless et al., 2025). Since high-resolution imagery of the surface of Mercury is not available, layering within the scarps is unresolvable. Thus, modeling the ability to produce scarps from fault-related folding can constrain the interpretation of Mercury's tectonic history while simultaneously understanding the effect that both layer thickness and gravity has had on the formation of these structures. This has significant consequences on the nature of global contraction and how much shortening the observed scarps can potentially compensate.

When applying fault-fold coupling types to thrust fault scarps on Mercury, it has been demonstrated that many scarps could be formed by shallow (< 5 km deep), low angle (< 10°), faults (Galluzzi et al., 2019) and suggested that the amount of potential shortening has been underestimated by 61-88% (Crane, 2020). Results were produced from a forward modeling approach which takes into account the fault angle, decollment depth, and gravity (3.7 m/s^2 on Mercury), as well as layer thickness, the depth at which the layering exists, porosity, and interlayer friction. A fixed shear modulus (i.e the relationship between the Young's modulus and Poisson's ratio for Mercurian crust) is also incorparated. These parameters are referred to as the "rigidity factor", which is similar to stiffness. In this way, the role of anisotropy in the formation of the observed fault scarps on Mercury can be specifically addressed.

The shear modulus was found to have several order magnitude less of an effect on the ability to fold than layer thickness, suggesting that these scarps cannot accommodate shortening by folding without layering. However, the lower Mercury gravity means that rocks are 2.4 times weaker than on Earth, meaning the required force for brittle deformation in Mercury's crust (as opposed to folding) is theoretically less than half that required on Earth. Layer thickness and fault scarp height were found to have an inverse linear relationship, whereas layer thickness and fault scarp width have a direct linear relationship. Additionally, from the variety of scarp sizes which can be produced from fault induced folding, the required slip rate is two orders of magnitude lower than the previously calculated 0.1-0.4 mm/y slip rate (Crane et al., 2017). Results show that layering along these fault scarps should be expected from high-resolution BepiColombo images, which will not be available until 2027. Otherwise, these scarps do not represent fault-bend/propagation folding and do not contain unaccounted surface shortening, but rather readily yield to brittle deformation.

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Drainage system evolution over a growing anticline: insights from the Maiella Mountain (Abruzzi, Central Apennines, Italy)

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Keywords: Geomorphometry, active tectonics, Maiella.

The landscape evolution of a region is dictated by the interplay of climatic, tectonic, and surface processes. These factors leave distinct geomorphic markers that are quantifiable with topographic metrics including local relief, drainage patterns, river profiles, channel concavity, steepness indices, and slope-area relationships. In particular, drainage basins on actively growing anticlines adapt to changes in surface slopes caused by fault nucleation, growth, and lateral propagation. Such basins capture evidence on the kinematics of folds and faults, highlighting deformation styles, rates of ridge propagation, and landscape development. In regions of active deformation, topography and drainage anomalies are key indicators of the interaction between erosion and tectonic processes offering insights into long-term mountain-building dynamics.

The Maiella Mountain offers an excellent opportunity to study the effects and linkage between surface and crustal processes on drainage system evolution. It formed from the eastward migration of the central Apennines chain-foredeep system, active from the end of the Early Pliocene onward, toward the Adriatic foreland. The mountain features a 35 km long NW–SE to N–S trending thrust-related anticline, with a gently plunging northern axial end and a steeper southern plunge. The eastern limb is bounded by a major west-dipping, east-verging thrust fault, whereas the western limb is cut by the west-dipping Caramanico Fault. Since the Miocene, this fault has accumulated over 3 km of offset near the fold culmination. Structural elevation reduces northward along with fault displacement. The stratigraphic succession is characterized at its base by Meso-Cenozoic carbonates overlain by Messinian evaporites and Lower Pliocene siliciclastic deposits. The top of the succession is characterized by tilted Pleistocene deposits that are unconformably layered atop the older formations. Despite extensive research on the Maiella Mountain, open questions persist regarding the timing and rate of uplift during the Plio-Quaternary period.

We present a geomorphological analysis of the Maiella Mountain providing new constraints on the evolution of the river network. In particular, we investigated and integrated general shape of topography (filtered topography, swath profiles, local relief), geometry of the hydrography (river longitudinal profiles, χ-plots, drainage divide mobility), and geologic data collected in the framework of the CARG project (Sheet n. 370 “Guardiagrele”). Finally, we inverted the longitudinal profile of the principal rivers draining the western and eastern portions of the Maiella Mountain to reconstruct their base level fall history. This approach provided crucial insights into the timing and uplift rates of the Maiella Mountain in the context of its progressive topographic rise, establishing a link between surface processes and deeper crustal dynamics.

Glacial dynamics in the south-eastern Alps during the LGM: evidence from the interaction between the Atesino and Monte Pasubio glaciers

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Keywords: glacial geomorphology, Last Glacial Maximum (LGM), Alpine glacier dynamics.

The Terragnolo and Posina Valleys, surrounding the Monte Pasubio massif in the south-eastern Alps, provide an ideal natural laboratory to explore cryospheric processes and glacial dynamics in response to climate variability during the Last Glacial Maximum (LGM) and Late Glacial. These valleys record a complex interplay between a major trunk glacier descending from the Adige Valley—the Atesino Glacier—and a smaller glacier forming an ice-cap on the Monte Pasubio massif.

The Terragnolo Valley runs east-west along the base of Monte Pasubio and curves NNW–SSE toward the Borcola Pass, creating a morphotectonic corridor that preserves a diverse suite of glacial deposits. Sedimentary facies reflect dual glacial influence: the Atesino Glacier is associated with polygenic, lithologically various deposits within the main valley axis and riverbed, while tributaries flowing from Monte Pasubio contain predominantly Triassic to Cretaceous carbonate-rich, glacigenic deposits. This distribution indicates distinct glacial domains and a complex interaction during ice advance and retreat phases.

By combining LiDAR-derived DTMs with detailed field mapping we were able to identify glacial landforms and sedimentary sequences, revealing phases of proglacial lake formation, sediment infilling, and drainage. Overconsolidated diamictons, located in central sectors of the Terragnolo Valley, support the interpretation of a lake basin that was later overridden by the advancing Atesino Glacier, which reached altitudes up to ~1400 m.

In the Valle dei Lombardi, a left tributary of the Terragnolo system, a well-developed lateral moraine sequence at around 700 m a.s.l. suggests a renewed advance of the local glacier after the trunk glacier's retreat. In the adjacent Posina Valley we found a buried paleosol beneath glacial diamictons. Ongoing dating on a wood fragment discovered in the paleosol will allow for chronological constraint on the Monte Pasubio glacier's maximum extent.

The spatial and temporal patterns observed point to a scenario in which the Monte Pasubio glacier had already reached significant development prior to the arrival of the Adige ice front. This raises important questions regarding local glacier autonomy and the potential overriding by the larger Atesino system. Enhanced orographic precipitation in the Monte Pasubio area likely favored early and sustained ice accumulation, highlighting the role of local climatic conditions in modulating glacial responses to regional climate forcing.

This study underscores the importance of integrated geomorphological and chronological approaches to deciphering cryosphere dynamics in the Alps. It contributes to broader efforts to understand how mountain glaciers respond asynchronously to climate drivers, and how local conditions may buffer or amplify regional climatic signals in glaciated landscapes.

Urban environmental geochemistry: a comparative soil study of Milan (Italy) and Swabi (Pakistan)

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Keywords: urban geochemistry, soil contamination, Milan and Swabi.

Urban geochemistry is emerging as a key discipline within the geosciences, offering essential tools to understand and mitigate the effects of pollution, resource use, and environmental degradation in urban areas. As such, the role of urban geochemistry is becoming increasingly central to addressing 21st-Century challenges, including soil and water contamination, public health concerns, and sustainable development. Urban soils, in particular, act as both indicators and reservoirs of anthropogenic pollution, making their geochemical analysis essential for sustainable urban planning, risk assessment, and environmental justice (Thornton, 1991).

This research investigates the geochemical composition of soils—both topsoil (0–20 cm) and subsoil (35–50 cm)—in two contrasting urban environments: Milan, Italy, and Swabi, Pakistan. Soil samples were collected using auger and spade methods within a systematic grid-based sampling framework (500 m × 500 m) across approximately 181 km² in each city, yielding over 800 samples per site.

The samples are being analyzed for more than 50 heavy metals and trace elements. A subset will also be tested for microplastics and major organic pollutants. For heavy metal and trace element analysis, samples are oven-dried at 40 °C, ground, and sieved through a 2 mm mesh. The sieved samples are digested with aqua regia and analyzed using inductively coupled plasma mass spectrometry (ICP-MS) at the Geochemical Laboratory, Department of Earth Sciences, University of Milano. For microplastic and organohalogen compound analysis, subsamples were separated prior to drying and freeze-dried.

Anthropogenic particles were isolated, and microplastics were identified via micro-Fourier Transform Infrared Spectroscopy (micro-FTIR). Organohalogen compounds were extracted and quantified using gas chromatography–mass spectrometry (GC-MS) or ultra-performance liquid chromatography coupled with Electrospray Ionization Time-of-Flight mass spectrometry (UPLC-ESI-TOF).

Here, we present the preliminary results of this study. Particular attention is given to the spatial distribution of contaminants and to comparing pollutant levels between cities with significantly different geogenic and anthropogenic sources of contamination. This research ultimately aims to contribute to the understanding of human impacts on urban soils and highlights the importance of environmental geochemistry in global sustainability efforts.

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Deciphering palimpsest alluvial landforms to constrain geological evolution: insights from the Taza-Guercif Basin, Morocco

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Keywords: geological maps, morphotectonics, rivers.

Palimpsest landscapes represent important archives of the geological evolution of a basin. The evolution of Neogene to present alluvial systems of North Africa remains insufficiently understood at present, although excellent exposure quality due to arid climate conditions allows for extensive mapping and 3D physical correlations. This study aims to describe the post-Messinian incremental landscape evolution of the alluvial systems at the southern margin of the Taza-Guercif foreland basin, located between the Middle Atlas and the Rif mountain belt and dissected by the Zobzit River, which has generated a succession of stacked terraces and paleovalleys. The multidisciplinary approach combines original geological and geomorphological mapping at 1:5000 scale, stratigraphic, sedimentological, geopedological, petrographic, and morpho-structural analyses, integrated with GIS-based processing and quantitative analysis of the DTM. Location of unconformable stratigraphic vs. conformable morphological boundaries, pinch-out and cross-cutting relationships among sedimentary units, the cannibalization of pre-existing alluvial clastics and colluvial wedges suggest drainage patterns responded to tectonics and/or major climate turnovers. The resulting maps and sections permit interpretation of the following evolutionary increments: i) northward-draining mountain front alluvial fans passing distally into extensive braid plains to coastal environment; ii) subsequent baselevel reduction generating a south-north trending axial braided river system, interacting with valley-confined alluvial fans incised into the preexisting braid plain and the Atlas highlands; iii) reorganization of the drainage system resulting from the progressive incision of the Zobzit River canyon following renewed baselevel fall, concentrating sedimentation within the axial river system and enhancing cannibalization of antecedent alluvial fan and river terraces. The ongoing research will constrain the sequential phases of landscape changes in the Taza-Guercif Basin to the tectonic and climate interplay from the Messinian to the present-day. Deciphering the nature, timing and hierarchy of successive episodes of landscape-changing events in such dynamic alluvial settings helps to constrain reliable evolutionary models. The latter are crucial for these arid regions, where river valleys constitute both primary sources of potable water and farmed areas.

S27.

Construction versus destruction processes at volcanic terrains

Conveners and Charipersons

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Probabilistic modeling of deposit-derived pyroclastic flows at Stromboli (Italy)

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Keywords: pyroclastic flows, Stromboli.

Stromboli (Italy) represents a natural laboratory for investigating the dynamic alternation of constructive and destructive processes in volcanic terrains. In particular, deposit-derived pyroclastic density currents (PDC) can result from the gravitational collapse of rapidly accumulated eruptive material in the upper portions of the island. These phenomena pose significant hazards, especially during Strombolian paroxysms, when deposit-derived PDC can propagate outside the Sciara del Fuoco - a prominent depression on the volcano's northwest flank.

We present a new analysis of these potentially impactful events by integrating historical records, new field observations, and advanced numerical modeling. The first phase of the study focused on reconstructing the most famous September 11, 1930, deposit-derived PDC, which was well documented but still affected by significant uncertainties. Recent erosive events revealed new deposits, especially in the San Bartolo valley, complementing known exposures and historical eyewitness accounts. These data enabled a first probabilistic reconstruction of flow paths, deposit thicknesses, and remobilized volumes, estimated between 34,000 and 59,000 m^3. A key insight from the modelling is the strong dependence of affected areas on the initial location of source material, and the complex interplay between some adjacent valleys, confirming the importance of terrain morphology in shaping destructive outcomes.

Building upon this reconstruction, we provided a first probabilistic hazard assessment for future deposit-derived PDCs at Stromboli. A novel approach utilizing random circular sector source modeling and temporal occurrence analysis was developed, also modeling the chance of multiple events in the same time interval. This model identified six key drainage basins with high remobilization potential and opening towards inhabited areas of Stromboli and Ginostra villages, where conditional spatial invasion probabilities reach up to ca. 28% at 50 m a.s.l.. Over the next 10 years, the mean probability of at least one PDC occurring outside the Sciara del Fuoco is estimated at 9%, rising to 49% over 50 years. Therefore, mean invasion probabilities in inhabited zones range up to 4% in a decade, increasing by a factor of seven over five decades. Despite inherent uncertainties due to the limited number of observed events, these findings emphasize the significant long-term hazard posed by deposit-derived PDCs at Stromboli.

Flank collapses at Stromboli volcano (Southern Italy): evidence from marine sediments record over the past 10,000 years

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Keywords: flank collapses, Stromboli volcano, marine sediments.

Active volcanoes represent morphologically unstable environments that are constantly evolving under the influence of constructive and destructive processes. Volcanic landslides represent a major geological hazard, with events such as debris avalanches, lahars, and explosive eruptions often being directly related to volcanic flank collapses of variable magnitude. In particular on volcanic islands, such instabilities have the potential to generate tsunamis, whose effects can propagate for hundreds of kilometers from the source.

An emblematic example is Stromboli volcano (Aeolian Islands, southern Tyrrhenian Sea), known for its predominantly mild, intermittent and explosive Strombolian activity. Several dykes and eruptive fissures are exposed along the flanks, evidence of intense intrusive activity that has shaped the morphology of the volcano over time. In the last ~10,000 years, several collapse events have affected the island, concentrating particularly along the Sciara del Fuoco (SdF), a horseshoe-shaped depression located on the northwestern slope. This structure acts as a collector for the material ejected during eruptive activity, making it prone to instability events. The SdF continues below sea level merging eventually into the submarine canyon of Stromboli. The deposits associated with subaerial and submarine gravitational events are often well preserved in deep marine sediments as sequences of volcanoclastic turbidites intercalated with hemipelagic mud and tephra layers.

Here we present a sedimentological and compositional study related to the first two meters of four marine cores collected at distances of ~31, ~43 (2) and ~44 km off-shore the SdF. The investigated time span covers about 10,000 years and date back to the collapse of Neostromboli, an event that marked the onset of the current eruptive activity. The aim of this study is to investigate frequency, age and magnitude of collapse events that have affected the volcano over the past millennia in order to assess the current hazard associated with these phenomena. The chronostratigraphy of the landslide events, as well as the time frame covered by the cores, was defined by the presence of datable primary tephra layers assigned to specific eruptions and by the compositional variability of volcanoclastic deposits. The analyzed compositions of the turbiditic deposits show a predominantly single-source origin, well compatible with current and past activity of Stromboli and are indicative of collapse events of different scale that have occurred on the island. Several turbiditic deposits can be correlated to outcrops found on-shore where primary tsunami deposits are preserved, suggesting that some of the associated collapse events have been tsunamigenic.

Unlocking Mount Melbourne's hidden record - First tephra characterisation from ice caves

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Keywords: Antarctica, tephra, geochemistry.

Mount Melbourne, is a quiescent volcano complex located in northern Victoria Land (Antarctica), characterized by persistent fumarolic activity that interacts with the overlying permanent ice and snow cover, giving rise to remarkable geothermal structures known as Fumarolic Ice Caves (FICs) and Fumarolic Ice Towers (FITs). These features form when hot volcanic gases, primarily H_2O and CO_2, escape from the ground, melt the base of the ice sheet, and condense as they reach the cold external atmosphere, forming complex cave systems and chimney-like towers. While this phenomenon has been studied in greater detail at Mount Erebus, Mount Melbourne and Mount Rittmann have been less explored, despite showing similar characteristics and the potential for significant volcanic activity, as deducted from tephra layers found at considerable distances.

We conducted the first-ever sampling of pyroclastic deposits (i.e. tephra) from three different ice caves of Mount Melbourne: MC1-Aurora, MC3, and MC4. These tephra samples, preserved in the cave environments, offer an exceptional opportunity to investigate past eruptive activity that may not be recorded elsewhere. The study focuses on the detailed analyses of tephra deposits found in these ice caves of Mount Melbourne. Investigations include textural observations as well as major and trace element geochemistry of single glass shards. The deposits are predominantly trachytic in composition, and their geochemical signatures strongly support an origin linked to explosive eruptions of Mount Melbourne.

The main goal of this study is to establish a direct correlation between subglacial and surface deposits, and to link the sampled tephra with other past activities from Melbourne Volcano.

This sampling within the fumarolic ice caves not only provides crucial data for understanding the eruptive history and volcanic hazards of the region but also opens new perspectivefor correlating Antarctic tephra between ice-bound and exposed volcanic systems.

The Palinuro Seamount: edifice collapse and growth in a submarine volcanic belt

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Keywords: submarine landslides, volcaniclastic fans, explosive volcanism.

Large part of the global volcanism occurs in the submarine environment, where plentiful volcanic seamounts dot the seafloor in various geodynamic settings. Recent studies show that submarine or insular volcanoes are subject to very rapid morphologic and magmatic variations. Fast volcanic growth often promotes flank instability and degradation, eventually culminating in sudden catastrophic collapses. In the Tyrrhenian Sea, many volcanic Islands and Seamounts are affected by mass-wasting processes with a wide range of size, and some of them show signs of past large edifice collapses. Landslides have been also recognized in the Palinuro Seamount (Passaro et al., 2011), part of the largest volcanic belt in the Tyrrhenian Sea (Marani & Gamberi, 2004; Cocchi et al., 2017). To further asses their role in the large-scale evolution of the Palinuro volcanic complex we have performed a re-analysis of multibeam bathymetric data and seismic lines. We recognize three main elements: degraded edifices, pristine cones with smooth flanks, volcaniclastic fans. The degraded cones are often truncated by prominent escarpments, which are interpreted as the lateral edges of large landslides associated with sector collapses. The lateral landslide escarpments are parallel or diverge downslope and affect large tracts of the degraded edifices. The area where they should join the landslide headwalls is the site of the pristine cones. This prevents the definition of the geometry of the headwall part of the landslides, but confirms that the pristine cones formed after the sector collapses. The flanks of the pristine cones are the proximal part of the volcaniclastic fans, which are a particularly prominent features of the southern slope of the Palinuro Seamount. They consist of a proximal part with a relatively flat seafloor connected to the pristine cones, a middle portion dominated by lobes and channels and a distal sector with predominantly large bedforms. We suggest that this arrangement is representative of a downslope transition from high-concentration to low-concentration turbulent flows, connected to explosive volcanism responsible for the growth of the pristine cones. In the northern Palinuro slope, on the contrary, the volcaniclastic deposits connected to the pristine cones are less extensive, and a rugged seafloor is the signature of the residual morphology of partially covered debris avalanche deposits. Our analysis emphasizes for the first time that repeated sector collapses are important in the volcanic evolution of the Palinuro seamount. Similarly to what observed for many volcanic seamounts, the Palinuro complex has a cyclic evolution whereby, large sector collapses form embayments in the proximal part of the volcanic belt and valleys further downslope. New volcanic centres form within the embayments, and produce abundant pyroclastic material, which fills the collapse scars and spreads as unconfined flows at the base of the edifice.

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Lahars on Stromboli volcano (Italy): first insights from field campaign

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Keywords: lahar, Stromboli, fieldwork.

Stromboli, one of the most active volcanoes in Italy, is characterized by a main eruptive activity consisting of persistent and mild explosions occasionally interrupted by more significant events named major explosions and paroxysmal eruptions. Due to such events, an abundance of erupted loose volcanic material emplaces on the upper steep slopes of the volcano and, after intense or prolonged rainfalls, is remobilized generating volcanoclastic flows of different typologies that invade lower slopes and, in several cases, reach the inhabited coastal areas of the island creating huge damages. The most recent example occurred in October 2024, when an intense rainfall, concentrated in a few dozen of minutes, rapidly remobilized loose pyroclastic deposits, triggering lahars with important volume that hit Stromboli and Ginostra village, as well as the access routes to the summit. The scale and intensity of these phenomena have revealed new hazard scenarios that were not fully considered in previous assessments. In order to investigate these events, a dedicated field campaign was conducted in April 2025 to characterize some of these deposits. Here we present the first results obtained both from fieldwork and from the laboratory analyses on collected samples. These results represent a solid starting point for implementing hazard scenarios related to lahar phenomena, which are fundamental for study their potential impact on inhabited and touristic areas of the island.

Age-clustered eruptive activity at La Palma (Canary Islands) during the last 4000 years: evidence from paleomagnetic dating

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Keywords: La Palma, paleomagnetic dating, basaltic eruptions.

The detailed knowledge of timing and dynamics of pre-historic eruptions is pivotal for volcanic hazard assessment. This is most relevant for inhabited lower slopes of active basaltic volcanoes such as La Palma (Canary Islands), where the 2021 Tajogaite eruption caused severe destruction. We paleomagnetically investigated eight La Palma Holocene eruptions which are currently loosely constrained either by few radiometric (K/Ar and ^{14}C) ages, or by stratigraphic/archaeological evidence. The paleomagnetic directions gathered from 28 sites (300 oriented cores) were compared with updated reference models of the paleo-secular variation of the geomagnetic field direction during the Holocene. Overlapping paleomagnetic directions from the Fuego and La Fajana lava flows, along with geologic and geochemical evidence, imply that the two flows were emplaced during the same eruptive event falling within the 2000–1730 BC time window. Single paleomagnetic age windows – consistent with and narrower than available 14C age intervals - were obtained for the Malforada–Nambroque, Montaña Quemada, and Fuego–La Fajana lava flows. Conversely, the Martín, Birigoyo–La Barquita, and La Caldereta flows yielded multiple age solutions. Moreover, our data show that the flanks of the pre-historic San Antonio scoria cone are almost totally covered by pyroclastic products of the nearby AD 1677 Fuencaliente eruption. The updated chronologic framework of the pre-historic volcanic activity at La Palma demonstrates that the past four kyr are characterized by an early period with low-frequency eruptions (three lava flow eruptions between ca. 2000 BC and 300 BC), followed by a ca. 1000 yr-long quiescence period, and by a subsequent clustering of nine events during the last 1100 yr (about one eruption per century).

Tephra Deposits as Chronostratigraphic Markers in the Tectonically Active Val d'Agri area (Southern Apennines, Italy)

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Keywords: Val d'Agri, tephra.

The Val d'Agri is a Quaternary tectonic depression located in the axial zone of the Southern Apennines fold-and-thrust belt. The ongoing extension is accommodated by both NE- and SW-dipping high-angle normal faults systems, bordering the two valley sides. The seismogenic role of these two fault systems is still debated: the source of the Mw 7 Basilicata earthquake in 1857 is not consensually defined; the anthropogenic seismicity related to the production activities of the Val d'Agri oilfield (the largest onshore oil and gas field in Europe), as well as the reservoir-induced seismicity (RIS) associated with the Pertusillo water reservoir, animate the scientific community.

Characterizing the Late Pleistocene-Holocene seismogenic activity of the SW-dipping East Agri Fault System is crucial. Along this fault system, we identify two volcaniclastic deposits draping the depositional surface of a Quaternary alluvial fan, appearing to be dislocated by dip slip faulting.

The first volcaniclastic deposit comprises three stacked units of fine to coarse grey ash: a ~ 72 cm thick massive basal bed, a ~ 37 cm thick finely laminated middle layer, and ~ 36 cm thick massive upper bed. All units are fractured and filled with calcite, with pervasive fracturing in the basal layer.

The second deposit, observed in a quarry wall, is a ~ 50 cm thick lens of yellowish sand, lying above bituminous calcareous conglomerate and beneath an epiclastic sand and present soil.

Tephrochronological investigation, including textural observation, glass geochemistry and Ar-40/Ar-39 dating, suggests that these tephra were derived from eruptions of Phlegrean Fields and Ischia. These tephra layers, once dated and correlated, apart from their contribution to the understanding of peri-Tyrrhenian volcanic activity, serve as valuable chronostratigraphic markers, offering key insights into the recent tectonic evolution of the Val d'Agri, providing estimates of slip rates, and contributing to resolve the ambiguity in designating the leading late Quaternary active faults of the Val d'Agri faults systems.

Paleomagnetic constraints on emplacement temperatures in phreatomagmatic deposits from the Astroni Volcano (Campi Flegrei, Italy)

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Keywords: phreatomagmatic eruptions, paleomagnetism, Campi Flegrei.

Phreatomagmatic explosive eruptions, triggered by the violent interaction between magma and external water, are among the most hazardous volcanic phenomena due to their proneness to generate highly mobile pyroclastic density currents (PDCs) with significant destructive potential. This eruptive style has played a pivotal role in shaping the volcanic history of Campi Flegrei (Italy), one of the largest and most densely populated active calderas on Earth.

Given the challenges in forecasting future eruptions, identifying key physical parameters that govern eruptive behaviour is essential, as they underpin numerical modelling and realistic hazard scenarios. Among these, PDC temperature is crucial, as it directly affects both lethality and destructive potential.

This study investigates emplacement temperatures of ~4 ka phreatomagmatic deposits from the Astroni volcano, a unique, well-preserved edifice, the only one in the Campi Flegrei caldera with closely spaced phreatomagmatic and magmatic eruptions. We conducted paleomagnetic sampling at ten sites, collecting twenty 0.3 cm to 4 cm-sized hand-samples per site, spaced across different stratigraphic units in both intra- and extra-crater outcrops. The flat surface of each sample was oriented by a compass and a clinometer. Paleomagnetic analyses show that:

1) 39% of lithic clasts exhibit two magnetic components: a randomly oriented High-temperature (HT) component, and a Low-temperature (LT) component aligned subparallel to geomagnetic direction expected 4 ka at Astroni according to the SHA.DIF.14K model (Pavón-Carrasco et al., 2014). Such clasts were reheated after deposit emplacement to temperatures between 190 and 470 °C, with a main cluster between 250 and 350 °C;

2) 42% of lithic clasts contain a single randomly oriented characteristic (CH) component, suggesting they remained colder than the lowest blocking temperature of the lithic clast;

3) 16% of clasts recorded a CH magnetic component aligned subparallel to the geomagnetic direction expected 4 ka ago at Astroni. These clasts, distributed heterogeneously across the sites, are interpreted as being hot (> 590 °C) before eruption, thus they are inferred to come from the deep magmatic system.

Based on the lowest recorded temperature at each site, emplacement temperatures were estimated to range from 220 to 280 °C for five sites, and 190 °C at one site. For the remaining sites, temperatures were estimated to be < 2 50 and 280 °C for two sites, and < 160 °C for the other two. Relatively low temperatures in ultra-proximal sites, both inside the crater and on the outer volcano slopes, consistently characterize the products of all Astroni eruptions. These findings contribute to a better understanding of the thermal variability within phreatomagmatic deposits, and represent significant data for improving predictive models of eruptive behaviour in complex caldera systems like Campi Flegrei.

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Giant phreatic eruptions at Milos Island (Greece)

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Keywords: phreatic eruptions, Milos island, Greece.

Phreatic eruptions rank among the most dangerous and enigmatic volcanic phenomena on Earth. Typically driven by the rapid vaporization of water due to heat and hot fluids from intruding magmas, these events result from the sudden conversion of thermal energy into mechanical work. Fragmentation of hydrothermal system host rocks and the subsequent ejection of particles lead to the accumulation of deposits that contain no fresh juvenile material. Milos Island (Greece), located in the central part of the Hellenic Volcanic Arc, hosts extensive hydrothermal systems in its eastern sector, where conditions are favorable for phreatic explosions. In fact, the island experienced several phases of phreatic activity during the Pleistocene. Our preliminary results have revealed evidence of at least two exceptional, giant phreatic eruptions of uncertain age (between ~100 ka and 1 Ma), which occurred within the Mesozoic–Palaeogene metamorphic basement. These eruptions produced eruptive units up to 50 meters thick, consisting of extremely poorly sorted, clast-supported angular lapilli and blocks (up to 1 meter in size), composed mainly of schists. We interpret these units as very proximal fallout deposits and extensive pyroclastic density current deposits, covering a minimum area of 15 km² (on land), with a maximum runout distance of 7 km from the inferred source. We believe this represents one of the largest, if not the largest, phreatic eruptions known to date. Further analysis is required to better understand the key factors controlling the preparatory state of both fluids and host rocks, as well as the mechanisms that triggered these remarkable eruptive events.

Insights on the multi-scale topographic features of Mt.Etna volcano (Italy)

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Keywords: terrain analysis, volcano, Etna.

The terrain analysis of volcanic landforms can provide valuable qualitative and quantitative insights into the factors controlling the shaping of volcanoes. Using different terrain analysis approaches, this study reconstructs and describes for the first time the multi-scale topographic features of Mt. Etna Volcano (Italy). Specifically, the first order shape of the volcano, approximating the large-scale volcanic edifice, is characterized through the analytical fitting of the contour lines using an elliptical geometry. The geometrical properties of this surface align with the evolution phases of Mt. Etna over the past 300 kyr. In particular, the geometrical parameters of the fitted ellipses such as the eccentricity, the position of the center, and the angle of rotation are clearly correlated with the evolution phases of Etna that contributed to the formation of the main volcanic edifice and that were distinguished on a stratigraphic base.

Furthermore, the modeled surface can be used as a two-dimensional filter: the residual topography, obtained by its removal from the actual topography, reveals second-order topographic features. The residual topography was then opportunely resampled and examined using the wavelet method along slope-parallel and base-parallel sections. This analysis identified zones with different wavelength behaviours which correlate with the residual topography anomalies. Their arrangement around the flanks of the volcano align with known volcanic features of Mt. Etna, such as the ‘’Ellittico’’ volcano and its caldera depression, the large volcano-tectonic depression of the ‘’Bove’’ Valley, and the unstable eastern flank. Other zones do not appear correlate to any recognized and may suggest the occurrence of buried features, target for future investigation.

This study demonstrates that the wavelet technique, when applied to terrain analysis on volcanoes, serves as a valuable tool for characterizing and classifying landforms.

S28.

Submarine evolution in volcanic settings and continental margins

CONVENERS AND CHAIRPERSONS

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Geomorphological and sedimentological characterization of the Ventotene and Santo Stefano insular shelf (Tyrrhenian Sea, Italy)

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Keywords: morpho-sedimentary characterization, volcanic insular shelf, Ventotene.

In the last decades, increasing studies on the submarine parts surrounding the volcanic islands have led important understandings about the past and present processes shaping the seafloor (Mitchell et al., 2002; Quartau et al., 2012; Casalbore et al., 2015; Innocentini et al., 2022). These contributions highlighted the importance to explore the marine areas to comprehend the geological dynamics acting on the submarine flanks of volcanic edifices which emerged portion represent only a small percentage. This study investigated the morphological and sedimentological characteristics of the insular shelf surrounding Ventotene e Santo Stefano through a multidisciplinary analysis including high-resolution multibeam bathymetries, side scan sonar mosaics and superficial sediment samples. Marine geophysical data were collected between 2000 and 2024 and analysed with cartographic software such as ArcGIS, Global Mapper, and QGIS, which allowed us to localize, observe, map, and measure the morphological features. On the insular shelf, several morphological features were investigated, including phanerogam meadows, rocky outcrops, extensive bioconstruction areas, submarine depositional terrace edges, pockmarks, escarpments, and calderic rims. These features were classified according to their geological origin, distinguishing between volcanic, tectonic, sedimentary, hydrodynamic, and biogenic processes. Grain-size and calcimetric analysis have been performed to investigate the distribution and characteristics of the sediments along the shelf, including the percentage of terrigenous and biogenic components. The result highlighted a significant increasing of the bioclastic fraction along the shelf towards the offshore and deeper areas. Bioclasts are primarily composed of fragments from bivalves, coralligenous formations, and red algae, reflecting the typical temperate climatic conditions of the region. The morphology and sedimentology of the study area are the result of both erosional and depositional mechanisms linked to the interaction of various geological processes, including volcanism, tectonics, and hydrodynamics. The findings of this study will significantly enhance our understanding of the processes occurring on the shelf, providing valuable insights that can inform future research aimed at managing territorial resources and constructing offshore infrastructure. Additionally, this work will be helpful in advancing strategies for the protection and conservation of marine habitats. Furthermore, it will contribute to the development of new geological maps at a 1:50,000 scale for the Italian national CARG project, supporting the ongoing efforts to update and refine the country's geological cartography.

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Submarine landslide susceptibility in the Ionian continental margins: a case study from the Squillace basin (Southern Italy)

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Keywords: submarine landslides, susceptibility, woe.

Submarine landslides are among the most significant marine geohazards, capable of triggering tsunamis, damaging critical submarine infrastructures, such as telecommunication cables and pipelines, and interacting with other geological and oceanographic processes. Understanding their distribution, triggers, and recurrence is therefore crucial for both scientific knowledge and to plan efficient hazard mitigation strategies. The Ionian continental margin of Calabria, located in Southern Italy, is a tectonically active region where submarine landslides are particularly widespread. Over the past 15 years, the scientific community has focused on hazard characterization using geophysical data, revealing that the area is extremely active. Despite this awareness, little is known about the spatial distribution of future submarine landslides. Within this context, the Squillace Basin, located offshore along the Ionian continental margin of the Calabrian Arc, stands out as a particularly compelling study area. This basin developed due to the subduction of the Ionian oceanic lithosphere beneath the European plate since the Neogene (Mangano et al., 2023). Its seafloor morphology has been shaped by intense Plio-Quaternary tectonic deformation and vertical movements (Zecchin et al., 2012). The physiographic features of the area include a narrow continental shelf, a complex and incised canyon system, and the widespread presence of recent submarine landslides bear witness to the dynamic nature of the margin and underline its potential as a source of geohazards (Ceramicola et al., 2024). These characteristics also highlight the necessity for detailed spatial analyses aimed at identifying the most susceptible zones. For the first time, a susceptibility map of the Squillace Basin has been produced, using an innovative methodological approach. This new framework combines high-resolution geophysical data with morphometric analysis to identify areas most prone to submarine landslides, offering valuable insights for future hazard assessments and risk mitigation strategies. To better understand submarine landslide susceptibility in the Squillace Basin, we apply a data-driven statistical approach using the Weight of Evidence (WoE) method. This probabilistic technique quantifies the relationships between known landslides and predisposing factors, enabling both the assessment of each variable's influence and the identification of spatial patterns where specific combinations of factor classes significantly increase susceptibility. While the WoE approach is widely used in terrestrial applications, its application to the submarine remains limited and presents challenges related to data quality, resolution, and spatial uncertainty. Nevertheless, the resulting susceptibility maps and statistical outputs offer valuable tools for scientific interpretation and for supporting future monitoring strategies and risk mitigation efforts along the Ionian Calabrian margin.

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Natural sea acidification caused by submarine gas emission: case study of Panarea hydrothermal system

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Keywords: hydrothermal system, methane, carbon dioxide.

Gases able to trap heat in the atmosphere are called greenhouse gases, among these there are carbon dioxide and methane.

Carbon dioxide, diffusing passively into global ocean surface waters, could locally be the reason of an increase in the partial pressure of the CO_2 and consequentely of a reduction in seawater pH. With the current rate of pH change standing at 0.015 units per decade (Haugan & Drange, 1996) it could be probable that by 2100 a global surface water reduction in pH of up to 0.5 units will occur. A chronic reduction of surface water pH to below 7.5 would be severely detrimental to the acid–base balance of many species.

Areas with naturally high CO_2 may serve as useful sites to predict the impacts of ocean acidification on coastal environments.

Such environments could become invaluable natural laboratories for ocean acidification research, closely mimicking potential future CO_2 conditions in a natural setting (Kerrison et al., 2011).

The Aeolian Islands host one of the most active submarine hydrothermal system in the Mediterranean Sea, characterized by numerous submarine hot and acid waters vents up to 130 °C and wide spread CO_2 and CH_4 emissions discharged troughout local tectonic structures even at low depths (5 - 30 m). These features make Aeolian Islands an ideal natural laboratory for the study of processes related to seabed CO_2 and CH_4 leaks, ocean acidification and warming.

In the framework of MACMAP (A **M**ultidisciplinary **A**nalysis of **C**limate change indicators in the **M**editerranean **A**nd **P**olar regions) project, investigated about: the CO_2, temperature and pH variations by long-term series data, acquired by the observatory settled offshore Panarea island (Longo et al., 2022); and quantified of carbon dioxide and methane transfer from the seafloor to the atmosphere in submarine hydrothermal field, sampling seawater column at various depths and gases directly from submarine vents in order to determine the geochemical characteristics of dissolved and bubbling gases. Dissolution of gas in seawater and pH values as low as 7.0 in collected water samples point out to acidic conditions within submarine hydrothermal field offshore Panarea Island. Aquiring data time series, is essential to understand oceanic processes from the surface to the oceanic sub-bottom.

In this framework also Methane could play a significant role. Methane fluxes from anthropogenic sources are well constrained while natural sources are weakly estimated. Among geogenic sources, estimations of methane fluxes coming from volcanic/hydrothermal areas are those quantitatively more inaccurate or overestimated. Recently estimations of CH_4 fluxes take in to account the microbial activity that drastically decreases the methane output. Some marine areas might release large amounts of methane from the seafloor being an additional source to the atmosphere. It's quantification may become an important goal in the very next future.

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Morpho-structural evolution of the Pantelleria volcano through the analysis of its submarine portions

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Keywords: submarine volcano, tectonic, mass-wasting.

Pantelleria island is located in the Sicily Channel, which has been generally interpreted as an example of intraplate "passive", NW-trending rift characterized by anorogenic volcanism (Civile et al., 2010). The island represents the upper part of a large volcanic edifice that raises for more than 2000 m from the northwestern sector of the Pantelleria Basin (Bosman et al., 2011). Pantelleria volcano is still active, with the last submarine eruption occurred in 1891 (e.g., Conte et al., 2014). In this work, we present an integrated analysis of high-resolution multibeam bathymetry, seismic data and seafloor samplings collected in 2006 and 2008 along the submarine portions of Pantelleria volcano. This analysis allowed to identify several geomorphic features related to volcanic, volcano-tectonic processes and erosive-depositional processes, also modulated by Late-Quaternary Sea level fluctuations. Volcanic features are lava flows and cones, while the interaction of volcanic and tectonic processes gives rise to elongated ridges, eruptive fissures, and steep fault escarpments. These features are aligned along the (main) SE-NW and (secondary) SW-NE directions, in agreement with the main regional tectonic lineaments observed in the Sicily Channel (Civile et al., 2010). Erosive-depositional features include insular shelf and overlying submarine depositional terraces, landslide scars, gullies, channels and upper-flow regime bedforms

Based on the different distribution and characteristics of geomorphic features among the Pantelleria flanks, an overall migration of volcanic activity from the SE to the NW sectors has been hypothesized. This migration is apparently in contrast with the development of a large insular shelf in the NW sector of the island, considering that shelf width is commonly used as a proxy for relative age reconstructions of volcanic edifices. This apparent discrepancy can be explained by interpreting the NW shelf as a polygenic feature, which formed in two main stages, the latter of which was characterized by shelf rejuvenation due to the large effusive activity occurred between 30 and 10 ka (Casalbore et al., 2024); ongoing petro-chemical analyses of the available samples will probably help to support this inference. Finally, the comparison of the depth of the insular shelf in the different sectors of the edifice provides new insights on the vertical movements that affected the Pantelleria volcano during the Late-Quaternary.

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Fault network geometries associated with the Campi Flegrei resurgence in the Gulf of Pozzuoli: an integrated analysis using 2D/3D high-resolution seismic reflection data

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Keywords: fault network geometry, UHR3D seismic data, NYT Caldera.

Volcanic and hydrothermal activity, together with caldera floor uplift (resurgence), within the Neapolitan Yellow Tuff (NYT) caldera of Campi Flegrei (Gulf of Pozzuoli), have been the subject of extensive investigations aimed at delineating the structural architecture and geological evolution of the system (e.g., Sacchi et al., 2014; Corradino et al., 2021; Natale et al., 2022). Nevertheless, the intricate geometry of the fault network—particularly in the apical sector of the resurgent dome—remains insufficiently resolved at metre scale. This limitation is the result of the inherent constraints of 2D seismic data, which often lack the spatial resolution and areal coverage required to accurately resolve fine-scale fault geometries. Additionally, such datasets are frequently compromised by seismic artefacts—most notably out-of-plane reflections—that obscure or distort the true configuration of subsurface structures. Moreover, the interplay between fault architecture and fluid migration, which may influence local stress distribution and potentially induce seismicity, remains poorly understood.

This study employs ultra-high-resolution 3D (UHR3D) seismic reflection data to investigate, at metre scale, the fault network geometry (including strikes, dips, and spatial extent) developed within the apical graben of the NYT resurgence. This new dataset is integrated with the analysis of 2D seismic reflection profiles, characterized by higher penetration depth, to enhance the understanding of the relationships between deep tectonic structures and shallow architectures.

Seismic interpretation and attribute analyses reveal a complex fault network comprising more than 60 predominantly normal faults, organized into distinct strike domains. Collectively, these structures define a radial-shaped geometry converging toward a focal point located at the centre of the resurgence, within the onshore sector. From west to east, the fault network displays three principal strike orientations: NE–SW, NNE–SSW, and NNW–SSE, with a subordinate set of ENE-WSW-trending faults.

Moreover, the presence of amplitude anomalies, bright spots, and localized velocity variations suggests that active fluid migration pathways sometimes exploit the fault network, crossing the main seismo-stratigraphic units.

This research refines knowledge on understanding the processes responsible for the formation of complex fault-network geometry and their potential as fluid conduits within the resurgence apical graben. The new findings underscore the critical importance of a multiscale analysis to accurately identify relationship of deep and superficial resurgence structures for improving forecasts of caldera behaviour during periods of unrest.

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Exploring the italian seamounts: unveiling deep-sea geological and biological settings

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Keywords: Mediterranean Sea, seamounts, ROV-imaging.

Submarine volcanoes, seamounts, and seamount-like structures are prominent seafloor features in the Italian seas (Pensa et al., 2019), hosting diverse and vulnerable deep-sea ecosystems enhancing biodiversity and ecosystem functioning (Würtz & Rovere, 2015). Due to their geological and ecological significance and vulnerability to anthropogenic impacts, seamounts are recognized as priority conservation targets (Clark et al., 2012, FAO, 2013). As part of the PNRR Marine Ecosystem Restoration (MER) project, an extensive exploratory campaign is currently underway to study 79 Italian seamounts located beyond 12 NM from the coast. The aim of the project is the improvement of our knowledge of the Italian seamounts, by using new geophysical and ecological data. A further goal is the assessment of the biodiversity of key benthic species and habitats down to 2,000 m depth. Different investigation instruments are used such as 1) multibeam echosounder (MBES), 2) sub bottom profiler Chirp (SBP), 3) remotely operated vehicles (ROVs), 4) acoustic doppler current profiler, 5) conductivity-temperature-depth profiler, and 6) grabs. The geophysical survey has started in April 2025 on board the S/V *NG Surveyor* in the southern Tyrrhenian Sea (Mediterranean Sea) and are to date still ongoing. Geophysical data are collected using Kongsberg multibeam echosounders (EM 2040 MKII, EM 712, and EM 304), a TOPAS PS18 sub-bottom profiler, a Sonardyne HiPAP USBL system. A BLS double grab sampler is employed to analyse the sedimentological parameters and the associated macrozoobenthic species. The geophysical data will be interpreted to reconstruct the morphological and environment of the seamounts. They will furnish the base to guide the successive phase of investigation, which will consist in a ROV work-class explorations to assess the presence and distribution of benthic species, improving our knowledge of the distribution of long-lived, slow-growing and vulnerable Mediterranean species. Moreover, this study will also provide valuable information on the distribution of key deep-sea habitats, supporting the creation of a network of marine protected areas, in line with the European Biodiversity Strategy 2030, the CBD and the MSFD objectives. The integration of diverse datasets, including geophysical and geological analyses, current-measurement data acquisitions, sampling of benthic organisms, and ROV-based observations, will enhances our understanding of submarine geomorphology, its relationship with marine species and the processes driving the evolution of underwater landscapes. The multi-scale and multidisciplinary approaches envisaged in this project provides the basis for a large-scale study of these environments, facilitating both the preliminary assessment of their geological risks and the planning for their sustainable management.

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Elaboration of thematic maps from the EMODnet Geology database

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Keywords: EMODnet, database, geological events.

The European Marine Observation and Data network (EMODnet) gathers existing data from seas surrounding European countries subdivided into thematic Lots. The Project Portal allows to freely browse through digital maps, standardized and harmonized at European scale, and download the underlying databases.

The geological Survey of Italy - ISPRA is Partner in the Geology Lot and coordinates the "Geological events and probabilities" work package, including submarine landslides, volcanoes, earthquakes, tsunamis, fluid emissions and Quaternary tectonics. Some of these features can be identified by the geomorphological elements they originate on the seafloor which are detected by geophysical investigations. However, it is important to note that the distinction between "process", "landform" and "deposit" is essential, although frequently, in common use, the same term is adopted for any of the three features (e.g. landslide). Furthermore, many terms are used by different communities of geologists to indicate different features or different terms are used to identify the same feature.

In EMODnet Geology, processes are collected within the "Geological events and probabilities" work package, whereas landforms are included into the "Geomorphology" layer of the "Seafloor geology" work package and deposits are considered within the "Seabed substrate" work package. Additional relevant information regarding bedrock composition can be retrieved from the "Seafloor geology" work package in the "Quaternary lithology" and "pre-Quaternary lithology" layers.

The combination of occurrences recorded by the different work packages may provide useful information concerning areas more subject to events which might have an impact on anthropic activities. The database gathered by EMODnet Geology cannot be used to perform any kind of direct analysis, but it represents a solid base to address further studies focused on geohazard assessment or land management.

A case study elaborated on the base of data gathered in EMODnet Geology is the "Structural map of seas surrounding Italy", in which the abovementioned data have been used to characterize the tectonic settings of submerged areas and visualize their geological evolution.

Plio-Quaternary features and evolution of the western Sardinian margin

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Keywords: reflection seismic profiles, tectono-sedimentary processes, margin tilting.

The evolution of the West Sardinian continental margin during the Plio-Quaternary (PQ) has received limited attention compared to other Mediterranean basins. This study reconstructs its tectono-sedimentary history by integrating multiscale reflection seismic profiles and bathymetric data. The seismic interpretation focuses on two key reflectors: the base of the PQ (Ms), corresponding to the end of the Messinian Salinity Crisis (MSC), and the base of the Quaternary (A0), identified through correlation with an interpreted seismic profile from the Gulf of Lion (Leroux et al., 2017). This allows the distinction between the Pliocene and Quaternary units across the study area, enabling the reconstruction of the margin's history.

Several features were identified: a) Salt tectonics, active since the late Messinian, has shaped both the deep basin through salt domes, and the lower slope through rollover structures, some of which are still deforming the seafloor; b) Plio-Quaternary normal faulting, linked to reactivation of Oligo-Miocene structures, appears to be driven by regional tilting and differential vertical movements; c) Volcanic edifices, including previously undescribed features, indicate two distinct magmatic phases. Subaerial erosion of some shelf volcanoes suggests episodes of emergence; d) Pockmarks, some of them active since the Pliocene, mark zones of fluid escape aligned with structural weaknesses on the outer shelf; e) Shelf progradations, characterized by sigmoidal clinoform geometries, indicate active sedimentation and shelf growth; f) Shelf-incising canyon systems (OCS, CCS and ACS), incise mainly Quaternary strata and appear to have developed recently in response to glacio-eustatic sea-level oscillations and margin oversteepening, challenging the hypothesis of a Messinian origin (Harris & Whiteway, 2011).

The observed features reflect the combined influence of tectonics, magmatism, sea-level fluctuations, and sediment dynamics in shaping the post-MSC evolution of the margin. The subdivision of the PQ sequence into Pliocene and Quaternary units in this sector is consistent with patterns observed in other Mediterranean basins (Selli & Fabbri, 1971; Volpi et al., 2017).

The margin's evolution has been influenced by vertical movements —subsidence offshore and uplift onshore— driving fault reactivation and controlling sediment pathways. Margin tilting, combined with high-frequency sea-level falls during the Quaternary, led to gravity-driven sediment instability, accelerating canyon formation. The sea-level variations also influenced the formation of the regressive clinoform system during the late Pleistocene in response to the seaward migration of the coastline.

Overall, this research offers new insights into the tectono-sedimentary architecture and dynamic processes shaping the west Sardinian margin, providing a solid basis for future high-resolution investigations of this margin and comparison with other Mediterranean margins.

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Submarine landslides, debris flows and canyons: processes of slope degradation and shelf-edge indentation in a tectonically active margin (Finale Basin, Northern Sicilian margin, Tyrrhenian Sea)

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Keywords: out-of-grade continental margins, continental slope, tectonic uplift and tilting.

Submarine canyons and landslides are closely related geological features of continental margins. The character of the linkage between submarine canyons and landslides varies depending on their geological and geodynamic setting. Consequently, a wide range of geomorphologies and processes, develop in association with landslides and canyons. They reflect different evolutionary pathways, which ultimately lead to continental margin degradation. The northern Sicilian Margin displays such a destructional setting, which is here exploited to study the role of landslides in canyon genesis and evolution. In particular, we address the study of the Finale Basin through the analysis of multibeam bathymetric data and seismic lines. We observe landslides unrelated with canyons with complex history and make up, which either indent the shelf edge or have their headwall in the lower slope. They are often associated to debris-flows. More importantly, however, we observe that the majority of the landslides relate with canyons. We recognize that depending on the style of the landslides two types of canyons develop. The worm canyons nucleate in the lower slope and develop through successive small landslides migrating upslope along narrow corridors. The racket canyons develop in the depressions created by larger landslides in the upper slope, and evolve through further downslope excavation due to debris-flow processes. Both canyon types can indent the shelf edge often in association with duck-feet bowls, triangular depressions that form the upper reaches of some of the canyons. The observations in our study area suggest that the northern Sicilian margin is reacting through canyon and landslide formation to out-of-grade conditions due to continental margin uplift and tilting. We show that canyons nucleation can occur either in the lower or in the upper slope. We imply that whatever the canyon type, debris-flows are the most important processes for slope excavation and canyon enlargement and propagation. Finally, we show that the processes that lead to shelf-edge indentation have a range of magnitude. Relatively large indentations form in coincidence with the canyon-generating landslide, smaller ones relate to the bowl-shaped source area of channelized debris-flow.

Pockmarks, mounds, and microbial activity in a hydrothermal lacustrine system: a case study from Pantelleria Island (Strait of Sicily)

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Keywords: pockmark, alkaline lake, geohazard.

Pockmarks are crater-like depressions formed by the release of subsurface fluids (Hovland & Judd, 1988). While they are well documented in marine environments, they remain poorly characterized in lacustrine settings (Hovland et al., 2002).

This study presents the first comprehensive morphological and geochemical investigation of over 100 pockmarks and around 200 mounded structures on the floor of Bagno dell'Acqua, an alkaline lake within the Cinque Denti Caldera on Pantelleria Island (Strait of Sicily).

High-resolution bathymetry, sub-bottom seismic profiling, SCUBA observations, and gas geochemical analyses were integrated to assess the origin and distribution of these features.

The pockmarks, predominantly elliptical and clustered in the lake's western sector, exhibit signs of active or recent gas seepage and are associated with seismic anomalies such as gas chimneys and acoustic blanking zones. These features likely formed through the upward migration of biogenic methane and hydrothermal CO_2 emissions. In contrast, mounded features, concentrated in deeper lake sectors, are interpreted as gas-charged domes formed by sediment uplift and hydrothermal mineral precipitation, often associated with active bubbling and microbial mats. Gas analyses reveal a blend of magmatic CO_2 and biogenic CH_4, underscoring the interaction of volcanic, sedimentary, and microbial processes.

These findings highlight the importance of lacustrine hydrothermal systems in fluid migration, microbial processes, and carbon cycling, and provide new insights into the geomorphological and geochemical evolution of Bagno dell'Acqua lake. The detection of active gas seepage indicates elevated geohazard potential associated with fluid overpressure and subsurface instability in volcanically and tectonically active lacustrine environments.

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The volcanic island of Corvo (Azores Archipelago) as a key study for understanding insular shelves development

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Keywords: volcanic ocean islands, marine erosion, mass-wasting processes.

Volcanic islands are the present-day subaerial remains of much larger volcanic edifices raised from the ocean floor. Their geological development is shaped by a complex interplay between volcanic, tectonic, erosional, sedimentary, and gravitational processes (Ramalho et al., 2013). As main volcanic activity wanes, destructive processes take over, shaping shore platforms which then evolve into insular shelves (Quartau et al., 2010). Although the subaerial portions of volcanic islands are relatively well-documented, their submerged flanks remain largely unexplored primarily due to limited direct observations, especially in remote oceanic areas.

To address such knowledge gap, this study investigates the volcanic island of Corvo from the western Azores. Its peculiarities, such as location, absence of natural barriers to prevailing waves, and geo-morphological simplicity, make the island an ideal natural laboratory for understanding shelf evolution under oceanographic conditions.

A multidisciplinary onshore-to-offshore approach was employed, by combining volcano-stratigraphy and coastal geomorphology with morpho-bathymetry, seafloor reflectivity (backscatter mosaic), seismic architecture, and seafloor sediment characterization. Corvo's shelf was mapped within the framework of the HAZARDOUS project (Evaluating HAZARDs related to the formation and development of detrital and lavic "fajãs" in the POrtugUese volcanic archipelagoS).

Corvo Island exhibits a rugged landscape, characterized by steep cliffs and an irregular shelf. The coastal-to-shelf system is classified into three distinct sectors – Western, Northern, and Eastern – each exhibiting unique morphological and sedimentary characteristics, alongside a southern lava delta extending from inland to the shelf edge. Seafloor is dominated by debris deposits from cliffs dismantling in the inner shelf and sandy sedimentary cover elsewhere. Sands are mostly volcaniclastics in nature, with extremely low bioclastic contribution. Deep clinoforms, cross-shore oriented bedforms on the island's lee side, and sediment distribution around the shelf suggest complex and high hydrodynamics. Ancient and present-day slope instabilities further shape the submarine landscapes.

Findings reveal that Corvo Island underwent a complex evolution due to intense marine erosion, leading to both subaerial and submarine mass-wasting events and the development of varied sedimentary facies. A reconstruction of the island's assumed original edifice was carried out to estimate the magnitude of volcanic material lost, erosion rates over time, and potential future scenarios.

This research offers valuable insights into the post-volcanic geomorphological and stratigraphic evolution of volcanic insular shelves, contributing to a broader understanding of processes affecting shallow submarine environments and with implications on coastal hazard assessments.

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Summit zone andesites and peripheral basalts at Marsili volcano (Tyrrhenian Sea)

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Keywords: volcano load, density threshold, bi-modal volcanism.

A number of large volcanoes that erupt evolved magmas in the focal region also present dominantly basaltic products at their periphery, even at several kilometres of distance from the volcano edifice. Examples include Mount Mazama, Mount Adams and Mount Hood in the Cascades, Toba in Sumatra, Kilimanjaro in Tanzania and Tenerife in the Canary Islands (Hildreth & Lanphere, 1994; Eichelberger & Izbekov, 2000; Pinel & Jaupart, 2000; Kent et al., 2010).

The submarine Marsili volcano shows a similar twofold behaviour. Sampling at various water depths indicate that the numerous small eruptive cones observed at depths > 2000m along the flanks of the Marsili volcano erupted basaltic lavas. Instead, eruption of evolved lavas, ranging from basaltic andesites to andesites in composition, appears to be confined to shallower depths (< 1000m) that define the summit rift zone (SRZ) of the volcano, with the andesites erupted at a limited summit portion of this zone.

Previous studies of volcanoes where such twofold behaviour is recognised, relate it to a variety of processes including the edifice load and the subsequent imposition of a magma density threshold, the stalling of basalt melt beneath fractionation shadow zones or the injection of basaltic dykes beneath the andesite focal zones.

It is suggested that the local conditions of the Marsili plumbing system, made of stacked and interconnected melt- and crystal-rich mush zones, have somehow controlled the magma transport conditions to allow the co-existence of basaltic andesite to andesite eruptions at the SRZ with basaltic magma activity focused at the peripheral zone, such as in other large volcanoes.

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Innovation in coastal monitoring: drone photogrammetry and geophysical survey methods for sicilian coastlines

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Keywords: geophysical technologies, drone photogrammetry, coastal monitoring.

Recent marine geophysical activities conducted by GEO BIO TEAM Group s.r.l. were based an innovative approach to collect data for understanding seabed topography, geological structures, and environmental dynamics. This methodology combines offshore investigations using Multibeam and Side Scan Sonar with onshore topographic surveys employing drone photogrammetry throughout two DJI quadcopters integrated with GNSS RTK positioning systems. The latter ensures precise centimeter-level accuracy in terrestrial data collection. Furthermore, the drone photogrammetry captures not only the emerged sectors and coastline but also acquires bathymetric data up to depths of 2 to 3 meters beyond the surf zone under favourable sea conditions (minimal wind, smooth water, and high seabed visibility). The novel approach ensures a continuous topo-bathymetric data coverage.

The integration of terrestrial and marine dataset was facilitated by the use of a Compact Survey Vessel (CSV), a newly acquired 3m x 1.6m amphibious craft. This vessel allows for real-time data control via an onboard pilot and a ground support station. Its high manoeuvrability makes it ideal for conducting geophysical surveys in coastal and lagoon environments where larger vessels face operational challenges.

This methodology was successfully applied in the frame of ongoing projects along the Sicilian coasts (e.g. Alcamo Marina in the north-western coast, Petrosino in the south-western coast and Marina di Ragusa in the south-eastern coast). For instance, the low-depth survey at Marina di Ragusa acquired morpho-bathymetric and backscatter data with a resolution of 0.05m on a submerged cable section using the Norbit Winghead i77h Ultra High Resolution 400kHz Multibeam system.

This innovative approach, integrating drones and lightweight vessels like the CSV, enables the collection of continuous, accurate, and reliable data. These datasets support ecological assessments, environmental impact evaluations, and the monitoring of submerged coastal infrastructure, as well as preliminary studies for cable and pipeline installations.

Evidence of recent morphological evolution of submarine volcanic environments revealed by repeated bathymetric surveys and ROV footage: Insights from Piscità Channel (Stromboli Island)

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Keywords: multibeam bathymetry, bathymetric changes, ROV exploration.

The steep submarine flanks of volcanic islands are strongly dynamic environments where eruption, slope instability and sedimentary processes combine to shape complex seafloor morphologies. Stromboli volcano, located in the Aeolian Archipelago, offers a unique natural setting to investigate these morphologies, thanks to its persistent Strombolian activity alternated with episodic lava overflows, crater rim collapses, and pyroclastic density currents. Most of the eruptive products are funnelled to the sea through the Sciara del Fuoco (SdF) collapse scar, a prominent subaerial-submarine depression along the NW flank of Stromboli. Part of this material (mainly the sandy fraction) can be transported from SdF in a clockwise direction around the island, nourishing the beaches on the N and NE side of the island (Romagnoli et al., 2006). Here, a large submarine channel (Piscità Channel) is present, whose headwall is located at shallow depths (< 10 m), less than 100 m far from the coastline (Casalbore et al., 2010). This means that the channel head can interact with coastal dynamics and intercept part of the sediment transported by the longshore drift (especially after major eruptive events), as testified by morphological changes recorded between 2002-2003 and 2013-2015 (Casalbore et al., 2017; Casalbore et al., 2021).

In this study, we present an integrated analysis of repeated multibeam bathymetric surveys and ROV video footages collected over the last four years, revealing significant morphological changes within the channel, associated with the development of retrogressive slope failures at its head (corresponding to the edge of nearshore submarine depositional terrace) and formation/reshaping of upper-flow regime bedforms within the downslope thalweg. These processes are likely due to severe storms that affect the island during winter months, representing a main trigger for sediment collapses and the generation of supercritical gravity flows.

These results highlight the need for a continuous and integrated monitoring of active channels to better understand the relationship between wave loading, sediment supply, coastal processes, and seafloor dynamics in volcanic island settings, with implications also for geohazard assessment.

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Advanced geophysical technologies for nearshore and offshore investigations: preliminary results from Apulian and Tuscan Platforms

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Keywords: multibeam bathymetry, Side Scan Sonar, reflection seismics.

This work presents advanced geophysical investigation techniques (i.e. multibeam, Side Scan Sonar, reflection seismics) and describes the preliminary results from surveys conducted as part of wind farm design studies across the nearshore and offshore of the Apulian and Tuscan platforms.

The aim of this research is the geomorphological and stratigraphic characterization of the study areas. Specifically, the objectives are: (1) Analyse seabed morphology using multibeam bathymetric surveys; (2) Determine seabed type using side-scan sonar acquisition techniques; (3) Reconstruct stratigraphy and identify tectonic structures through the analysis of seismic profiles; (4) Assess biodiversity through video inspections.

The oceanographic surveys were conducted in the summer of 2024 aboard the M/B Orca 2 in the nearshore and the M/V Denar Explorer in offshore. Bathymetric data were acquired using the Multibeam Norbit Winghead B41 in nearshore and Multibeam Kongsberg EM71 in offshore, Side Scan Sonar data were obtained through the Klein 3000, and seismic profiles were acquired using the GeoPulse Compact (Chirp source) and Geomarine Mini-Spark 1000 (Sparker source) in nearshore and Edgetech 2300 (Chirp source) and Geomarine Geo-Source LW400 (Sparker source) in offshore. Visual inspections were conducted uisng the "Observation Class" SAAB Falcon Seaeye 12399 ROV in nearshore and the "Work Class" SubAtlantic Tomahawk model from Forum Energy Technologies in offshore, equipped with cameras with a resolution of 480 TVL.

Multibeam data revealed erosive features such as canyons, channels, ripples, slope failures, sliding deposits, sea mounts, pockmarks and zones with rocky substrates.

Side Scan Sonar data allowed the distinction of areas with fine sediment, sandy, and rocky substrates. Additionally, traces of anthropogenic activities (trawling, presence of traps for catching crustaceans, archaeological remains) were identified.

ROV video inspections included both targeted inspections at specific points and a biological study of the benthic species. The navigated transects were selected based on the interpretation of acquired geophysical and geological data. The recordings revealed areas colonized by biocenoses of calcareous benthic organisms (encrusting "coralligenous" type) as well as areas characterized by predominantly muddy substrates.

High-resolution and ultra-high-resolution seismic profiles enabled the stratigraphic and structural characterization of the sites, identifying pockmarks, fluid presence, erosive features (e.g. gullies), contourite deposits, landslide deposits, volcanic substrates, and carbonate mounds.

The integration of geophysical techniques combined with visual inspections provides an extremely detailed knowledge framework of the marine environment. The data obtained represent a fundamental basis for geological and environmental research, as well as for the sustainable management of marine resources and the protection of underwater heritage.

Constraining palaeo sea levels on the Liguro continental shelf: a geomorphological approach based on high-resolution bathymetry and seismic data

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Keywords: marine terrace, seafloor landform, sea-level index point.

Continental shelves preserve a complex suite of submerged landforms related to past sea-level fluctuations, that can be reconstructed by merging multibeam bathymetry and seismic data. Along the Liguro-Provençal continental shelf, this integrated approach provides a precise representation of landforms evolved in a subaerial environment prior to the Last Glacial Maximum, mantled by deposits formed during the transgressive stage of the Lateglacial-Holocene sea-level rise (Raffa et al., submitted). Some of these landforms have formed in a littoral environment and have been preserved in response to sea-level changes. In this work, we analyse one type of these features, i.e. the marine terraces mapped along the continental shelf in the area between Imperia and Nice. According to the standardized methodology for paleo sea-level reconstruction (Shennan et al., 2015; Rovere et al., 2016) each marine terrace was converted into a sea-level index point. In absence of direct chronological constraints on the terraces, possible timing of their formation is inferred based on relative sea-level change model predictions available for the area. Our results reveal the presence of multiple terrace levels at comparable depths in geographically distinct areas between Imperia and Nice. Their position and mutual relationship will also be analysed with reference to the structural features of the Liguro-Provençal shelf, its recent tectonic evolution, establishing chronostratigraphic correlations with sea-level fluctuations. The results provide evidence to refine model predictions and improve our understanding of the tectonic contribution to relative sea-level change in the area.

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Spatial and temporal pockmark formation and migration in the Civitavecchia continental slope (Central Tyrrhenian Sea)

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Keywords: pockmark, morphometric analysis, seismostratigraphy.

Pockmarks are sub-circular seabed depressions formed by fluid flow processes at the seafloor. They are among the most common morphologies associated with fluid flow along continental margins (Spatola et al., 2025). However, the mechanisms controlling their formation, spatial distribution, and temporal migration remain debated, especially in passive margins. This study investigates the spatial and temporal evolution of 238 pockmarks identified along the Civitavecchia continental slope in the northern Latium continental margin (Central Tyrrhenian Sea) using high-resolution geophysical data (seismic reflection and multibeam bathymetry).

The study area, divided into two morphologically distinct sectors, displays a high concentration of pockmarks, with axis ranging from 10 to over 200 meters and depths of up to 7 meters. Morphometric analysis enabled the classification of the pockmarks into two main categories, “normal” and “giant”, based on standardized size criteria (Hovland et al., 2002). The observed forms have strong geometric consistency, suggesting similar formation conditions.

Seismo-stratigraphic interpretation allow us to identify ten main stratigraphic surfaces many corresponding, according to the interpretation of Fraccascia et al. (2013), to erosive discontinuities and their correlative conformities linked to 100-kyr Quaternary eustatic cycles. Pockmarks are preferentially located within depositional units associated with sea-level lowstands highlighting a possible eustatic control on their genesis. Hydrostatic pressure changes during sea-level fall likely promoted the upward migration of overpressurized fluids, triggering pockmark formation.

Additionally, acoustic anomalies in the subseafloor recognised by using the seismic data (e.g., chimneys, wipe-out zones) and local sediment deformation suggest active and/or recent fluid flow systems, likely involving free gas within shallow sediments. Pockmark distribution also appears influenced by seafloor morphology and bottom currents, oriented NNW-SSE, which may have acted as a secondary control, fostering pockmark migration and alignment.

In conclusion, our findings highlighted that pockmark formation and spatial distribution along the Civitavecchia slope result from the interplay between fluid flow dynamics, eustatic cycles, and the local geological factors (e.g. tectonics and bottom currents). This study can easily contribute to a better understanding of the controls on fluid seepage in passive continental margin and provide an evolutionary model potentially applicable to other equivalent geological settings.

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An integrated multiscale approach to investigate the seafloor in continental shelves (Sicily Channel, Italy)

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Keywords: seafloor morphology, pockmarks, clean energy.

The growing potential of offshore technologies is turning the submarine environment into an increasingly strategic area for clean energy infrastructure development. The seafloor is shaped by biological, geological, and oceanographic processes. Therefore, its detailed characterization is fundamental for identifying hazards that may affect anthropogenic installations, as well as for predicting environmental impacts. Since the last century, the Sicily Channel has been extensively exploited by the Oil & Gas companies, which have dealt with its complex morphology and active tectonics. Previous studies have documented the occurrence of pockmarks mainly along tectonic structures. However, many areas are still unexplored – a geomorphological and structural analysis would be pivotal for the implementation of new clean energy infrastructures. This study presents an integrated analysis which combines 2D deep reflection seismic lines from VIDEPI project (http://www.videpi.com), with a recently acquired high frequency dataset from the Sicily Channel, off the coast of Pozzallo (RG). The latter includes multibeam echosounder bathymetric data, Side Scan Sonar (SSS) profiles, Remotely Operated Vehicle (ROV) imagery, Sub-Bottom Profiles (SBP). The integration of seismic data at different scales allows the analytical evaluation and mapping of geomorphological features. The new interpretation reveals several small depressions (up to 1 m in diameter) in the seafloor. Seismic attributes (e.g., envelope) help to distinguish moat-drift systems—resulting from bottom currents—active/quiescent pockmarks, as well as anthropogenic activity marks. Such an integrated approach is effective for a detailed geomorphological and structural characterization of the seafloor, which is essential for assessing geohazards and vulnerable areas. Furthermore, this work will contribute to defining the guidelines for the implementation of new offshore infrastructures in the area of interest.

A comprehensive geodatabase of mediterranean sea pockmarks: advancing marine geomorphological analysis

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Keywords: pockmarks, geodatabase, fluid flow.

We present a georeferenced database of pockmarks distributed across the Mediterranean and the Black Seas, compiled from a range of marine geophysical techniques, including multibeam bathymetries, backscatter data on the seafloor and in the water column, seismic reflection profiles (Spatola et al., 2025). In the study area, pockmarks are among the most common seafloor morphologies associated with fluid flow processes of the continental margin, with densities reaching up to 3.4 features per km2. Pockmarks have diverse morphologies, ranging from sub-circular to elongated in planar view, and typically display U- or V-shaped cross-sectional profiles (Hovland et al., 2002). From 1970 to date, over 6,000 scientific documents indexed in Scopus were published as original articles. Our dataset integrates spatial information for over 7,500 pockmarks reported in recent scientific literature, forming a centralized, systematically organized repository of pockmarks. The primary novelty of this study lies in the development of comprehensive and detailed repository of information on pockmarks. The database offers broad applicability: it can inform the development and management of offshore infrastructure (e.g., pipelines, wind farms), guide ecological assessments (e.g., identification of habitats supporting sensitive benthic communities), and support resource evaluation (e.g., hydrocarbons, gas hydrates, offshore groundwater). Moreover, it can serve as a valuable tool for advancing research on marine geosystems and the dynamics of fluid migration within the seafloor.

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S29.

Multiple stressors across land-sea transitional environments: assessment methodologies and technological advancements

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The role of sedimentary environment in the development of coastal hypoxia phenomena: some examples from Baltic and North Seas

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Keywords: hypoxia, coasts, seafloor.

With more than 500 oxygen-depleted systems recognized worldwide, hypoxia and anoxia are amongst the most pressing threats for shallow coastal and shelf seas (Whitney, 2022). Lagoons, estuarine and coastal shelf sediments worldwide are exposed to enhanced anthropogenic nutrient inputs, often resulting in depleted dissolved bottom oxygen concentrations, characterized by a high benthic mortality (Van Colen et al., 2009).

The effect of bottom oxygen scarcity depends on climatic and hydrodynamic conditions as well as by depositional characteristics of the seafloor itself and of the substrate (Alvisi & Cozzi 2016). Within the framework of MEBox project, we have investigated the role of the seafloor in the generation of hypoxic/anoxic events in coastal and lagoon areas of Belgium (Zwin Park) and Poland (Puck Bay) by applying a methodology developed for the NW Adriatic Sea (Alvisi et al., 2013).

The Zwin is the largest and most significant tidal salt marsh site in Belgium. It is part of the Natura 2000 network and was expanded in 2019 by removing the international dike, allowing the tidal system to extend over an additional 120 hectares of former agricultural land. Sediment samples for geological investigation (n. 18 sites) and meiofauna experiment (n. 4 sites) were collected in 2021 in the Zwin Natural Park (Belgian North Sea) with manually inserted 25 cm long PVC cores.

The Bay of Puck is a shallow western branch of the Bay of Gdańsk in the southern Baltic Sea. It is separated from the open sea by the Hel Peninsula. The bay has an average depth of 2 m to 6 m. There is a shallow sandbank in the middle of Hel Peninsula. The Puck Bay was sampled by scuba divers at 8 stations.

The sampling stations were selected according to different depositional characteristics (i.e., water depth, inner/outer position, ecc.) and bottom oxygenation conditions. Each core was analysed for lithological and sedimentological characteristics, grain size, TOC, TN, C and N stable isotopes and geochemistry. The very top 5-6 cm were subdivided into SUP samples (i.e., more oxidized and hydrated) and SUB samples (i.e., more compact and reduced). Then a couple of further layers were sampled along the record according to the layering. Some significant cores were subsampled along the entire length.

The results for the Zwin area converted to a tidal plain show a large lateral variety of depositional environments typical of low gradient muddy tidal flats. In all cases, however, the sampled sediments show thick hypo/anoxic levels, whether muddy or sandy. In Puck Bay, the cores sampled below 4 m depth in the two main pits show a sedimentary record characterized by anoxia. The shallower cores are sandier, gravel rich and more oxidized in correspondence of the two thresholds that connect the lagoon to the bay, while the sand is finer, clearer and cleaner at the site located on the North side of the lagoon near the sandbank of the Hel peninsula.

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Initiation of tidal channels: insights from deposits of the Venice Lagoon (Italy)

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Keywords: tidal channels, tidal bar, Venice Lagoon

Tidal channels are a common feature in tidal systems, playing a key role in regulating the transport of water, sediment, nutrients, and particulate matter in coastal environments. In recent years, growing attention has been given to the bio-morphodynamic processes driving the evolution of tidal channels. However, the mechanisms governing their initiation and early development remain poorly understood. This study focuses on tidal channels draining salt marshes in the Venice Lagoon (Italy) and explores whether these channels originate directly on the marsh surface or represent inherited morphological features from tidal flats that later transformed into salt marshes through biogeomorphic feedbacks triggered by vegetation encroachment and colonization.

The Venice Lagoon is the largest brackish water body in the Mediterranean, with an average tidal range of approximately 1 meter. It is a tide-dominated environment, as sediment inputs from fluvial and marine sources are negligible. Salt marshes in the Venice Lagoon are cut through by dense networks of branching tidal channels that display well-defined meandering patterns at sub-meter spatial scales. This study focuses on point-bar deposits associated with channels ranging from 0.5 to 3 meters in width, aiming to characterize the geometry of the bar bodies through sediment core analysis along transects aligned with the meander bend axes. Across 33 study transects, the comparison between bar geometry and the stratigraphy of surrounding overbank deposits -r eflecting a transition from tidal-flat to salt-marsh environment - offers valuable insights into landscape evolution during channel formative stages. Core analysis reveals four main types of deposits, namely: salt-marsh, point-bar, channel-lag, and tidal-flat deposits. Correlating these deposits along transects enables the reconstruction of bar geometry and identification of the timing and location of bar initiation in the stratigraphic record.

Our results indicate that most point bars originate at the transition between salt-marsh and tidal-flat deposits. This suggests that erosive processes began carving the surface during the early development of marsh vegetation - dense enough to stabilize sediments and support initial channel incision and bar formation, yet still too sparse to provide sufficient resistance to prevent erosion.

Decadal shoreline evolution and wetland vulnerability in the Ombrone Delta (Tuscany, Italy): a multitemporal analysis of coastal dynamics using satellite imagery

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Keywords: Ombrone Delta, shoreline changes, satellite imagery.

The Ombrone Delta, situated along the Tyrrhenian coast in southern Tuscany, within the Maremma Regional Park, represents an example of a wave-dominated deltaic system characterized by prominent beach ridges and wetlands hosting high biodiversity. The shoreline of the delta has historically alternated between progradational and erosional phases, influenced by littoral drift, wave climate and anthropogenic alterations to sediment supply (Bellotti et al., 2004). Several studies have investigated the geomorphological evolution of the Ombrone Delta, documenting significant shoreline erosion, particularly during the 19th and 20th centuries (e.g., Bellotti et al., 2004). Among them, Tarragoni et al. (2015) provided a detailed reconstruction of shoreline dynamics up to 2010. While these studies have widely contributed to the understanding of long-term coastal dynamics in the area, the increasing vulnerability of the adjacent wetland systems highlights the need for further investigation focused on more recent shoreline evolution. This study contributes to this effort by integrating geomorphological and geospatial analysis to assess shoreline changes between 2010 and 2024, to evaluate potential impacts on the surrounding coastal wetlands. Seven high-resolution satellite images (SPOT and Pléiades) were selected at 2-3-year intervals, with higher frequency in 2023 and 2024 to capture recent variations. The wet-dry shoreline boundary was digitized in ArcGIS Pro and processed using the standalone version of the Digital Shoreline Analysis System (DSAS; Himmelstoss et al., 2024). A total of 277 transects, spaced at 50 m, were used to calculate statistical parameters relevant to shoreline change analysis (Bheeroo et al., 2016), including End Point Rate (EPR), End Point Rate Uncertainty (EPR UNC), Net Shoreline Movement (NSM), Linear Regression Rate (LRR) and Linear Confidence Interval (LCI). Analysis shows increased erosion in the northern sector, near the river mouth and "Chiaro Grande" wetland, with the erosional front migrating northward in recent years. As a result, both the "Chiaro Grande" and more northerly "Chiaro del Porciatti" wetlands, located directly behind the eroding beaches and crucial for local biodiversity, are increasingly threatened. Conversely, the southern sector of the delta appears generally more stable than the northern one, a trend that may be attributed to the coastal defense structures built since 2011, which seem to mitigate erosion in this area. However, some erosive events have also been observed in this sector over the years, indicating that local hydrodynamic conditions may periodically challenge its stability. In conclusion, this study provides insights into the recent evolution of the Ombrone Delta, highlighting the potential impacts of ongoing erosion on wetland systems and the importance of continuous monitoring to support effective coastal management strategies.

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Evaluating longshore sediment transport: A comparison between empirical formulas and XBeach 2DH numerical model

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Keywords: longshore sediment transport, XBeach 2DH numerical model, coastal erosion

Longshore sediment transport (LST) is a crucial process shaping coastal environments. As multiple site-specific factors (e.g. wave height, coastal topography) influence the LST, an accurate estimation of LST rate represents a scientific challenge.

This research evaluates the predictive capacity of three widely used empirical formulas (CERC, 1984; Kamphuis, 1991; Van Rijn, 2014) and the XBeach 2DH numerical model for estimating the LST rate by comparing the obtained results with field LST data.

We chose three coastal sites in Malta Island (Għadira Bay, GB) and northern Sicily (Cefalù, CF, and Campofelice di Roccella, CR) based on different sediment grain size, coastal type (open or embayed) and morpho- bathymetry.

For each site, we analysed wave parameters, grain size of the beach and seabed sediments, coastal morphology, and marine vegetation distribution. Furthermore, we used field measurements to calibrate the numerical model's sediment transport and morphological parameters.

The calibrated numerical model provides greater accuracy in LST rate estimation than the empirical formulas. The latter overestimates the LST rates by factors ranging from 435 to 7885, whereas the numerical model overestimates by factors of 1.8 and 1.9 at the CF site and GB, respectively, and underestimates by a factor of 0.5 at the CR site.

The good performance of the numerical model is due to its consideration of site-specific factors. The parameter values for the model calibration can be used successfully in embayed fine/coarse sandy beaches. Moreover, the numerical model, tested so far only for sandy beaches, also works well on gravelly beaches.

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Coastal vulnerability assessment of pocket beaches: a comparative approach for Għadira Bay, Malta

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Keywords: coastal vulnerability index, erosion, pocket beaches.

Pocket beaches are often perceived as less vulnerable to erosion due to natural protections such as headlands that limit sediment exchange. However, this assumption has not been thoroughly tested across various methods of coastal vulnerability assessment. This study focuses on evaluating the vulnerability to erosion of pocket beaches by testing three different vulnerability assessment methods: a traditional approach, a method proposed by de Andrade et al. (2019), and a novel approach introduced in this research.

The Traditional method uses indicators such as Morphological Characteristics (e.g. width of the emerged beach, presence of dune systems and geomorphology), Wave Height, Geology and Shoreline Displacement. The de Andrade et al.'s (2019) approach incorporates morphological and hydrodynamic indicators, including Terrain Elevation, Wave Exposure, Wave Power, Incidence Angle, and Run-Up. The method Proposed in this study integrates three key indicators: Morphological Characteristics (e.g. width of the emerged beach, presence of dune systems, headland length, seabed slope and *Posidonia oceanica*), Cross-Shore Sediment Transport, and Long-Shore Sediment Transport, with the latter two being calculated through the XBeach 2D numerical model.

These methodologies were applied to Għadira Bay, a pocket beach located in the northern part of Malta. The results from all three approaches revealed varying levels of vulnerability. The Traditional method indicated high vulnerability across the beach, while de Andrade et al.'s (2019) approach provided an overall moderate vulnerability assessment. The method Proposed in this study showed a consistent moderate vulnerability throughout all sectors.

These findings suggest that, contrary to previous assumptions, pocket beaches like Għadira Bay are indeed vulnerable to coastal erosion. The comparative analysis highlights that the Traditional method tends to overestimate vulnerability, de Andrade et al.'s (2019) approach offers a broader, averaged assessment, and the Proposed method provides detailed, sector-specific insights. Moreover, the proposed approach quantifies sediment transport, allowing predictions of future shoreline evolution. This provides insights for effective coastal management and infrastructure planning, particularly for systems like pocket beaches.

de Andrade T.S. et al. (2019) - Vulnerability to beach erosion based on a coastal processes approach. Applied Geography, 102, 12-19, https://doi.org/10.1016/j.apgeog.2018.11.003.

Quantification of Sb and associated PTEs mass loads discharged by the Tafone creek in the Tyrrhenian Sea (southern Tuscany Sb province)

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Keywords: antimony, potentially toxic elements, mass loads.

Antimony is an economically important metalloid, but its mining can negatively impact the surrounding environment decades after mine decommissioning. Antimony was extracted in Southern Tuscany until the 1980s, and the legacy of Sb and associated potentially toxic elements (PTEs) persists in the water downstream of the abandoned mining areas that eventually pours into the sea. This study was conducted to quantify the mass loads of As, Hg, Sb, and Tl that are discharged by the Tafone Creek into the Tyrrhenian Sea in different hydrological conditions. A salt dilution method was employed to calculate the discharge flow at two sites downstream of the Tafone mine (one in proximity and the other close to the Sea) and one upstream in low and high flow conditions. Potentially toxic elements were analyzed in filtered (i.e., dissolved) and unfiltered water samples. During the summer period, the total concentration of As exceeded the maximum limit in drinking water recommended by EPA and WHO (10 µg/l) only at the site immediately downstream of the mine. The concentration of Sb exceeded the limit recommended by EPA (6 µg/l) downstream the mine, while it exceeded the limit set by WHO (20 µg/l) only at the site directly after the mine, where it reached 83.3 µg/l. Conversely, Hg and Tl concentrations did not exceed the limits set by EPA (2 µg/l for both elements) and WHO (6 µg/l for Hg, no specific guideline exists for Tl). Mercury transport occurs predominantly as particle-bound Hg at all sites (up to 4 mg/kg in particulate), although it progressively deposited downstream. Interestingly, dissolved Hg concentration increased compared to the particle-bound fraction at greater distance from the mine. In low flow conditions (0.3-0.6 L/s), the total mass loads of As, Sb, Hg, and Tl flowing in the site close to the sea were calculated to be less than 1 g/day; in the closest site to the mine area, however, the mass loads of the same elements increased, though remaining less than 1 g/day, except for Sb which reached 2.4 g/day, suggesting additional contribution from undiscovered Sb bodies and/or other mining sites. These preliminary results highlight that the Sb mass load of the Tafone catchment to the Tyrrhenian Sea is at least 10 times lower than Paglia and Fiora catchments (Rimondi et al., 2014; Nannoni et al., 2025), which are characterized by prevalent Hg mineralizations. Higher mass loads may be expected during rain events and episodic floods which are expected to occur more frequently due to climate change. New data recently acquired during high flow conditions will contribute to elucidate this topic.

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Nannoni A. et al. (2025) - Toxic trace elements transport in stream sediments from the world-class Monte Amiata Hg mining district: Potential impact to the Mediterranean Sea. Environmental Pollution, 372, 126088.

Petrographic analysis and coastal sediment dynamics: a multidisciplinary approach at the Sibari Site (BERMS PRIN-PNRR Project)

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Keywords: Ionian sands, grain-size distribution, petrography.

Within the framework of the BERMS project, the coastal zone of Sibari (northern Ionian Sea, Calabria) has been identified as a key location for examining sandy beach dynamics influenced by both natural processes and human activities. This area, shaped by wave-dominated conditions and a complex sedimentary framework, provides a valuable setting to explore sediment sources, transport mechanisms, and shoreline morphological changes (Cianfalone et al., 2018).

Grain-size distribution analysis, heavy mineral identification, and petrographic thin-section observations were carried out to trace lithological inputs and understand sediment transport pathways.

Preliminary petrographic analysis of the sandy fraction from samples collected along beach-to-sea transects reveals a predominantly siliciclastic composition, with only a minor carbonate component. The detrital assemblage is dominated by quartz, feldspars (both K-feldspar and plagioclase), and micas. Lithic fragments primarily consist of phyllites, gneisses, medium- to high-grade micaschists, amphibolites, and amphibole-bearing schists. These characteristics suggest a mixed felsic and mafic provenance for the clastic material.

The main detrital modes were combined with geomorphological surveys, elevation profiles, and geophysical surveys - such as Ground Penetrating Radar and electrical resistivity imaging - to interpret sediment distribution in relation to coastal landforms and substrate characteristics. This multidisciplinary methodology makes it possible to establish the mass balances, characteristics of depositional environments, and susceptibility to erosion of a such crucial area as the Sibari coast in the Ionian area.

By integrating detailed petrographic data with broader environmental information, this site-specific research contributes to the broader aims of the BERMS project, which seeks to develop adaptable strategies for beach monitoring and coastal management throughout Mediterranean regions.

Cianflone G. et al. (2018) - Late Quaternary stratigraphic setting of the Sibari Plain (southern Italy): Hydrogeological implications. Marine and Petroleum Geology, 97, 422-436.

From urban protection to ecosystem preservation: insights and challenges from the Venice Lagoon, Italy

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Keywords: coastal hazard, storm-surge barriers, ecosystems.

Increasing hazards from rising sea levels and extreme weather events are compelling coastal communities to implement adaptive strategies to protect their settlements from flooding risks. Hard-engineering structures, such as storm-surge barriers and floodgates, are increasingly being proposed to protect and sustain the socio-economic functioning of at-risk areas, with 18 major projects completed worldwide to date (Mooyaart & Jonkman, 2017). However, while storm-surge barriers are effective in mitigating flood risks, their impacts on hydrodynamics and ecomorphodynamics are a closely related concern (Orton et al., 2023).

Here, we focus on the flood-regulated Venice Lagoon, Italy, where a storm surge barrier system, known as Mo.S.E. (an Italian acronym for "*Modulo Sperimentale Elettromeccanico*"), has been operational since October 2020 to mitigate flood risk in Venice City and the surrounding lagoonal settlements. Using hydrodynamic numerical simulations, we compared the impacts of different flood-regulation scenarios by analyzing the spatial and temporal extent of flooding in both Venice City and the surrounding salt marshes, where maintaining appropriate flooding depth and duration is crucial for their resilience. Specifically, we simulated tidal and wind-wave-induced circulation patterns, comparing the real-case flood regulation with a hypothetical non-regulated scenario, and a third, hypothetical, scenario featuring optimized floodgate management to minimize closure frequency and duration (Mel et al., 2021).

Our analysis reveals a critical imbalance in the coastal management of the Venice Lagoon. While storm-surge barriers have proven effective in protecting lagoonal settlements from flooding, water levels were excessively reduced - 30% below local safety thresholds, on average - thereby limiting or preventing salt marsh flooding and related sedimentation. However, hindcast analyses indicate that about 30% of the Mo.S.E. activations were unnecessary, as lagoonal settlements would not have been flooded even if the floodgates had remained open.

Our results confirm previous findings on the negative impacts of water level regulation on salt marsh ecosystems (Tognin et al., 2021), despite its effectiveness in reducing urban flood risks. Although the floodgates are operated only 1–2% of the year, their intervention may have decreased marsh sediment accumulation by approximately 56%. Nonetheless, we demonstrate that a balanced management strategy could simultaneously protect urban settlements from flooding while enhancing the ecological resilience of salt marsh ecosystems to sea level rise, increasing sedimentation by up to 25% compared to the current flood-regulated conditions. These findings provide significant insights for the future global management of coastal areas, promoting sustainable development while addressing societal, economic, and environmental needs.

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Mooyaart L.F. & Jonkman S.N. (2017) - Overview and Design Considerations of Storm Surge Barriers. Journal of Waterway, Port, Coastal, and Ocean Engineering, 143(4), https://doi.org/10.1061/(asce)ww.1943-5460.0000383.

Orton et al. (2023) - Increased Utilization of Storm Surge Barriers: A Research Agenda on Estuary Impacts. Earth's Future, 11(3), https://doi.org/10.1029/2022EF002991.

Tognin et al. (2021) - Marsh resilience to sea-level rise reduced by storm-surge barriers in the Venice Lagoon. Nature Geoscience, 14(12), 906-911, https://doi.org/10.1038/s41561-021-00853-7.

Preliminary assessment of saltwater intrusion in the Volturno coastal plain (Southern Italy): a multidisciplinary case study

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Keywords: saltwater intrusion, coastal aquifers, sustainable water management.

Saltwater intrusion represents one of the most serious and growing threats to coastal aquifers, particularly in areas affected by intense urbanisation and extensive irrigated agriculture. This phenomenon is the result of a progressive advancement of seawater into groundwater systems, due to an imbalance between the rates at which water is recharged and withdrawn. The process is exacerbated by climate change (i.e., sea-level rise), local subsidence and reduced natural recharge and can compromise the quality of water resources for human consumption and agriculture, with potentially irreversible consequences for soil productivity and coastal ecosystem integrity.

The Volturno River coastal plain (Southern Italy) provides a representative example of this critical dynamic in an area of outstanding environmental and economic interest. Over the past decades, a combination of intensive groundwater abstraction, land subsidence, and human induced changes has led to the progressive deterioration of groundwater quality and marked inland advancement of the saltwater (Alberico & Matano, 2024). Some previous studies have highlighted the complexity of the local hydrogeological system and the coexistence of active marine intrusion with residual paleo-salinisation using numerical modelling, geophysical, geostatistical methods, and environmental tracers (Gaiolini et al., 2023; Tarallo et al., 2023; Colombani et al., 2024).

Against this backdrop, a new technical-scientific initiative has recently been launched with the SAL.WE. Project, jointly developed by CNR-ISMAR (National Research Council - Institute of Marine Sciences) and ABDAM (Basin Authority of Southern Apennines District,) through a Collaboration Agreement (ex-art. 15 L. 241/90), which is funded with resources from FSC 2014-2020. This activity is part of a broader ABDAM action of 'Interventions to improve the quality of water bodies' in compliance with Directive 2000/60/EC. The SAL.WE. Project aims to enhance the spatial characterisation of saltwater intrusion through an integrated and replicable approach. Studies include analyses of coastal plain stratigraphy and geology, hydrological features, subsurface hydrogeological setting and ecological features, as well as analyses of shoreline evolution, subsidence processes, meteorological, climatic and sea wave parameters. Current activities include electrical resistivity tomography (ERT) surveys, groundwater and surface water sampling, measurement of key physic-chemical parameters (e.g., conductivity, salinity) along selected coastal transects and meteorological monitoring.

Preliminary results allow for an initial delineation of the areas affected by saltwater intrusion and the construction of a baseline knowledge framework for vulnerability analysis. This will support the implementation of long-term monitoring systems and the design of sustainable groundwater management strategies. This study is presented as a case study that is potentially applicable to other Mediterranean coastal aquifers under similar hydrogeological and ecological stress conditions.

Alberico I. & Matano F. (2024) - Subsidence and recent landscape evolution at Volturno Coastal Plain (Italy). Quaternary International, 712, 109584, https://doi.org/10.1016/j.quaint.2024.11.00.

Colombani N. et al. (2024) - Unravelling the salinity origins in the coastal aquifer/aquitard system of the Volturno River (Italy). Water Research, 263, 122145, https://doi.org/10.1016/j.watres.2024.122145

Gaiolini M. et al. (2023) - Seawater intrusion assessment along the Volturno River (Italy) via numerical modeling and spectral analysis. Journal of Hydrology, 626(Part B), 130289, https://doi.org/10.1016/j.jhydrol.2023.130289

Tarallo D. et al. (2023) - Geophysical assessment of seawater intrusion: The Volturno Coastal Plain case study. Applied Water Science, 13, 234, https://doi.org/10.1007/s13201-023-02033-x.

Mapping *Posidonia oceanica* banquettes using Unmanned Aerial Systems (UAS)

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Keywords: Unmanned Aircraft System, banquettes, Favignana Island (Sicily).

Posidonia oceanica banquettes represent an important habitat in terms of biodiversity and ecological functions, including the reduction of the waves' energy for beach stability. However, a detailed characterization and mapping of banquettes are missing in many Mediterranean coastal areas. In 2021, ISPRA carried out the mapping of a P. oceanica banquette in Favignana Island (Sicily) adapting the UAS photogrammetry already used for other marine habitats. DJI Mavic 2 Pro drone by RGB camera was used. Flight plans were made with Pix4D Capture software. Altitude and flight speed were adjusted to have an image overlap of 80% (models with a ground resolution of 1.5 cm); 12 ground control points were surveyed using an RTK GNSS differential receiver system. Images were processed with the Agisoft Metashape software for the generation of dense point clouds, Digital Surface Model and the orthomosaic then used for the subsequent automatic of banquette recognition with the machine learning algorithm by Trimble eCognition Essential Software.

An accurate thematic map of the banquette was obtained, including data on the total area, volume and stability. Results confirmed the high suitability and usefulness of UAS photogrammetry for banquette characterization, suggesting its possible application for wider monitoring programs along the Mediterranean shores.

Monitoring and management of *Posidonia oceanica* banquettes by using a GIS-based approach at the Mediterranean basin level

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Keywords: gis, banquettes, susceptibility map.

Posidonia oceanica (L.) Delile is a marine phanerogam, endemic to the Mediterranean Sea. Its fallen leaves occur naturally along Mediterranean coasts constituting either temporary or permanent structures (the so-called banquettes). These deposits can influence shoreline morphology, nutrient cycling, and coastal ecosystem functioning, highlighting their ecological and geomorphological role in the coastal processes (Tomasello et al., 2022 and references within). Nevertheless, the banquettes perception by the different stakeholders (beach managers, local administrations and tourists) is often negative; they consider these deposits a smelly waste to be removed, rather than a natural and valuable component of the coastline system (Rotini et al., 2020). Furthermore, there is no comprehensive knowledge of the geographical distribution of banquettes as detailed characterization and mapping of banquettes are missing in many Mediterranean coastal areas. Their mapping is essential for coastal management and conservation efforts, at the scale of the entire Mediterranean basin coasts. For all these reasons the implementation of a geographic information system (GIS) can be extremely useful for P. oceanica banquettes monitoring at the Mediterranean basin scale, that, in the long run, may help for the understanding the complex process of beaching, including implication for coastal erosion.

The present work, GIS based, has implemented a Marine Coastal Project and has georeferenced the P. oceanica deposit sites collected through a detailed systematic literature review (available between 2000 and 2024) at the Mediterranean basin scale, with a special focus on Italian coasts.

A total of 353 sites of interest have been currently considered and a synoptic map was implemented in order to show the P. oceanica deposit and banquette occurrence along the entire Mediterranean coastline. This overview mapping can provide an important basis for future mapping and analyses aimed at understanding the biological, sedimentological and geomorphological patterns involved in beaching processes.

In addition, this GIS approach can provide important contributions to support local and national administrators in making data-driven decisions by visualizing spatial relationships, patterns, and trends. This approach can improve the challenging management of the banquettes by combining the needs of touristic exploitation of the beaches and the protection of coastal ecosystems and coastal erosion issues.

Tomasello A. et al. (2022) - 3D-Reconstruction of a Giant Posidonia oceanica Beach Wrack (Banquette): Sizing Biomass, Carbon and Nutrient Stocks by Combining Field Data With High-Resolution UAV Photogrammetry. Marine Ecosystem Ecology, 9, https://doi.org/10.3389/fmars.2022.903138.

Rotini A. et al (2020) - Effectiveness of the "Ecological Beach" Model: Beneficial Management of Posidonia Beach Casts and Banquette. Water, 12(11), 3238, https://doi.org/10.3390/w12113238.

Embedding compaction processes in long-term evolution of the Venice Lagoon. A 2D analysis on representative vertical sections

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Keywords: transitional landforms, Holocene evolution, numerical modelling.

The spatiotemporal evolution of transitional landforms, such as river deltas and coastal lagoons, is intrinsically linked to sediment accumulation and (auto)compaction. These two natural processes significantly affect their thickening and surface elevation with respect to the mean sea level. As new sediments accumulate on the top surface, the underlying soil is compacted under gravitational load over time. This work aims to provide a comprehensive 3D (i.e., 2D in space, including time) perspective to address this issue, incorporating data interpretation techniques and novel numerical modeling tools that account for the dynamic interplay of sedimentation and compaction. Advanced simulators, based on finite element or virtual element approaches are used to simulate the evolution over the Holocene of a few exemplificative sections of the Venice Lagoon, Italy. The complexity of sedimentation-compaction history is explored by combining 2D seismic lines, lithologic borehole logs, and sediment geochronological data. This information, coupled with the geomechanical properties of lagoon deposits derived from field and laboratory testing, forms the primary input to the simulators. The simulators combine a 2D groundwater flow module with a 1D compressibility module to reproduce the Holocene evolution of the domain using adaptive meshes, properly simulating accretion and natural consolidation, which govern the dynamic thickening and elevation evolution. The models are calibrated to match the present-day lagoon topography/bathymetry, and provide estimates of current natural compaction rates resulting from Holocene evolution. Furthermore, they can be used as tools to evaluate future land subsidence and quantify the sedimentation needed to maintain saltmarshes at their present elevation relative to a rising mean sea level driven by climate change.

Acknowledgments: This work is part of the RESTORE (REconstruct subsurface heterogeneities and quantify sediment needs TO improve the REsilience of Venice saltmarshes) research program, a PRIN 2022 PNRR Project funded by the European Union – NextGenerationEU.

Sediment and surface water geochemistry interactions along a pronounced W-E salinity gradient: natural areas of the Po River Delta (Italy)

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Keywords: climate change, coastal system, geochemistry and salinity gradient.

The Interreg Italy-Croatia ACTION project (2024-2026) aims to understand the resilience of coastal ecosystems and promote adaptation strategies to address climate change. Within this framework, a focus is placed on the Po Delta (Italy), where a new hydraulic management system is set to be implemented to restore the water cycle in the natural coastal areas of the northern Ravenna municipality. This study presents the results of a recent fieldwork campaign combined with a comprehensive review of both published and unpublished data. The aim is to better understand water-sediment geochemical processes and interactions across transitional environments, from freshwater to saltwater systems. Over the past six months, sediment and surface water samples were collected from 16 distinct water bodies—including ponds, drainage canals, rivers, lagoons, and wetlands—to assess major and trace element compositions. Previous geochemical data from the same matrices were used as a reference for temporal comparison.

Bulk sediment composition, analyzed via XRF, reveals a wide range of SiO_2, CaO, Fe_2O_3, LOI, and various trace elements, indicating complex sediment provenance, depositional environments, and localized human influence. The Mg/Ni ratio has proven effective in distinguishing sediment provenance, using river sediments as endmembers. Furthermore, stratified sediment samples from multiple sites show high Enrichment Factors (EF), highlighting significant anthropogenic impacts on sediment geochemistry. Arsenic, lead, copper, and vanadium exceed Italian legislative thresholds at several locations, particularly in surface sediments, due to recent industrial discharges, intensive agriculture, and urban runoff. Surface water geochemistry reveals a complex hydrological system with a pronounced W-E salinity gradient. Calcium bicarbonate-dominated river and drainage waters (Ca-HCO_3) rapidly mix with sodium chloride-dominated saltwater (Na-Cl), leading to significant changes in ionic strength. These shifts affect the dissolution and precipitation equilibria of several dissolved elements, subsequently influencing sediment composition. By examining these water-sediment interactions, this study expands scientific knowledge on the interplay between natural and anthropogenic factors in the study area, providing insights into the effects of climate change on coastal ecosystems.

Small vessel wakes in a channel-shoal system: preliminary results from an experimental and modelling study

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Keywords: Venice Lagoon, wave measurements, maritime traffic.

Hydrodynamic processes play a crucial role in the morphodynamics of transitional systems, by governing sediment redistribution and the formation and stability of erosional and depositional patterns. In particular, shallow regions such as shoals and saltmarshes are especially subject to the effect of waves, which are one of the main factors controlling their stability and evolution. While wind is obviously the main driver for waves in relatively pristine environments, vessel traffic can also add up to a potentially significant extent to wave activity in densely anthropized systems.

In the present study we investigate the dynamics of small boat wakes in shallow water environments in order to assess the contribution of maritime traffic as a morphological stressor. A field campaign was carried out in two channel-shoal systems in the northern Venice Lagoon characterised by low traffic (and therefore good control on the experimental conditions), morphological diversity (sloping shoal flanked by a neighbouring saltmarsh vs. broad, unconfined mudflat), and the availability of recent morphobathymetric data. A set of Kelvin wake patterns generated by a 7-metre motorboat in different sailing conditions were measured by high-frequency (16 Hz) pressure gauges deployed in different configurations in the study sites.

A simple application of linear wave theory on the measured data allows a first estimate of vessel-induced energy input into the system and its potential for morphological disturbance. Moreover, a set of high-resolution numerical experiments, currently underway, can expand the observations and provide a more detailed description of wake propagation, paving the way to dedicated upcoming developments on the implications of this process for sediment transport and landscape evolution.

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Improvements to restoration projects in the Venice Lagoon salt marshes

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Keywords: salt marshes, autocompaction, finite element modelling.

We present a modelling approach to investigate the elevation dynamics of a saltmarsh restoration project in the central basin of the Venice Lagoon, Italy.

A key aspect of salt marsh restoration design is determining the long-term elevation of the marsh platform, which is critical for the ecological functioning of the system. It is well known that the long-term survival of salt marshes hinges on their ability to keep pace with relative sea level rise (Morris et al., 2002). Unfortunately, a significant portion, although not quantifiable due to a lack of a monitoring strategies, of newly created saltmarshes in the Venice Lagoon have rapidly degraded and are now mostly submerged or have not developed proper halophytic vegetation, making them more vulnerable to erosion. We hypothesize that two critical factors have not received sufficient attention: (i) the autocompaction, i.e., the natural process by which sediments compact under their own weight over time, of the newly-disposed dredged sediments and (ii) the subsidence of the pristine lagoon bottom due to autocompaction of the Holocene deposits.

To address this knowledge gap, we studied a saltmarsh restoration area of approximately 61,000 m² confined with a wooden pole sediment barrier and nourished with a fluid sediment-water mix. After performing a 10-m core to investigate the nearby soil stratigraphy, we developed and installed a custom-designed monitoring system to study the autocompaction of the newly-disposed dredged sediments and the subsidence of the pristine lagoon sediments. Monitoring data collected between 2021 and 2024 have been interpreted using a state-of-the-art Finite Element geomechanical model (Xotta et al., 2022). The model simulates autocompaction within both the pristine lagoon deposits at the saltmarsh restoration site and the newly-disposed dredged sediments. The modeling results serves as a key foundation for designing and optimizing best management practices, particularly regarding the target land elevation required to support effective saltmarsh restoration.

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Xotta R. et al. (2022) - Modeling the role of compaction in the three-dimensional evolution of depositional environments. Journal of Geophysical Research: Earth Surface, 127(9), e2022JF006590, https://doi.org/10.1029/2022JF006590.

S30.

Monitoring the Earth for Hazards: Integrating Geology, Geophysics, and Risk Assessment

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Environmental risks, resilience and sustainability: the Rome metropolitan area study case

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Keywords: Rome metropolitan area, environmental risks, sustainability.

The metropolitan area of Rome, whose territory coincides with the former province, extends on a surface of 5,353 km^2 and hosts about 3,400,000 inhabitants. It represents, in terms of extension and demographic indicators, the first Italian province and the third European metropolis. From 1870 to 2014, the local authority in charge of governing such wide area was the Province of Rome; from 2015, its functions were taken over by the Metropolitan City of Rome (CMRC), after the reorganization of the administrative structure of Local Authorities resulting from Law 56/2014.

The CMRC can boast of a long tradition of care for knowledge of territory, functional to the protection of infrastructures and urban areas, due to the historical provincial duties about roads and school buildings. Since 1870, after the annexation of Rome to new Kingdom of Italy, the Province payed thus attention towards geological issues and disaster prevention. Provincial roads and high school buildings still today represent the real property exposed to natural and anthropic risks. The particular geological setting of Rome metropolitan area, corresponding to the Thyrrenian margin of Central Apennines, determines in fact the presence of a wide range of natural hazard, including landslides, flooding, treefall, subsidence, sinkholes, gas emissions, earthquakes, roars (Argentieri et al., 2024) and even tsunamis.

For this reasons, in modern times the Province established with foresight, as early as the 1980s, a Civil Protection Survey, and then a Geological Survey (Argentieri et al., 2018), in order to ensure disaster prevention and specialized support to its technical offices. CMRC continues the ancient tradition of study and knowledge of its territory for the same purpose, dealing with technical and administrative problems about land governance and infrastructure management. Moreover, CMRC promotes initiatives of divulgation and information campaigns for safety culture and environmental education (Argentieri et al., 2019).

This contribution presents the state of the art of actions, carried on by CMRC autonomously or in partnership with other institutions, for soil protection, land management, environmental conservation, civil protection, sustainable development, prevention of natural and anthropogenic risks, instrumental monitoring and infrastructure safety.

Argentieri A. et al. (2018) - Natural and anthropogenic cavities and sinkholes in Rome metropolitan area: from geological and speleological research to land management. Rend. Online Soc. Geol. It., 44, 104-111.

Argentieri A. et al. (2019) - Replace fear of the unknown with curiosity: natural risks and culture of prevention in the metropolitan area of Rome. Rend. Online Soc. Geol. It., 49, 85-93.

Argentieri A. et al. (2024) - Tanto rumore per qualcosa: i misteriosi brontídi - Much ado about something: the misterious "brontídi". Acque Sotter. - Ital. J. Groundw., AS51-844, 67-71, https://doi.org/10.7343/as-2024-844.

MILQ and SLIDEQ: online platforms for evaluating soil liquefaction and earthquake-induced landslide triggering in Italy

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Keywords: seismic hazard, soil liquefaction, seismic landslides.

In this study, we present two web services for the evaluation of the triggering potential of two major earthquake-induced effects in Italy: soil liquefaction and landsliding. The former, called MILQ (https://distav.unige.it/rsni/milq.php; Barani et al., 2023), allows verifying if, at a given site, the triggering condition proposed by the Italian Guidelines for Seismic Microzonation (hereinafter, ICMS) (SM Working Group, 2008) are met – namely, if the expected seismic events are characterized by moment magnitude values $M_w \geq 5$ and produce a surface peak ground acceleration $a_{max} \geq 0.1$ g. Similarly, the latter, called SLIDEQ (https://distav.unige.it/rsni/slideq.php; Azhideh et al., 2024), uses the ICMS criterion for landslide triggering to verify if seismic landsliding at the site of interest can be discounted – specifically, if the expected seismic events are characterized by magnitude and source-to-site distance values above the well-known upper-bound curves for seismic landslide triggering proposed by Keefer (2002). Both tools rely on the reference Italian seismic hazard maps and the associated hazard disaggregation. We consider disaggregation results corresponding to different response periods, so to account for possible resonance effects. More specifically, the reference magnitude (*M*) or magnitude-distance (*M*-*R*) scenarios are selected so that the spectral period considered in the disaggregation analysis is compatible with ground response (i.e., geological conditions), which is considered through the soil types defined by the Italian building code.

For a specified location (defined by a pair of geographic coordinates), MILQ and SLIDEQ, which were developed in "PHP" and "HTML5" languages according to current web standards, return the values of *a*max and *M* and those of the *M*-*R* pair corresponding to different failure mechanisms (disrupted slides and falls, coherent slides, and lateral spreads and flows), respectively. As the actual soil type (and, in the case of MILQ, also the topographic class) of the site of interest can differ from that stored in the database used by MILQ and SLIDEQ, our services allow the user to modify it according to site-specific information and return the updated values of *a*max-*M* and *M*-*R*.

Our portals can be useful to land-use planners in deciding whether liquefaction and seismic landslides are hazards that need to be considered within urban planning processes or not. Furthermore, they can serve as a guide for recommending focused geological and geotechnical investigations aimed at the evaluation of liquefaction hazards and assessing landslide susceptibility.

Azhideh S. et al. (2024) - Earthquake-induced landslides in Italy: evaluation of the triggering potential based on seismic hazard. Appl. Sci., 14, 3435, https://doi.org/10.3390/app14083435.

Barani S. et al. (2023) - Evaluation of liquefaction triggering potential in Italy: a seismic hazard-based approach. Nat. Hazards Earth Syst. Sci., 23, 1685-1698, https://doi.org/10.5194/nhess-23-1685-2023.

Keefer D.K. (2002) - Investigating landslides caused by earthquakes – A historical review. Surv. Geophys., 23, 473-510.

SM Working Group (2008) - Indirizzi e criteri per la microzonazione sismica. Conferenza delle Regioni e delle Province autonome – Dipartimento della protezione civile, Roma, https://www.protezionecivile.gov.it/it/pubblicazione/indirizzi-e-criteri-la-microzonazione-sismica.

Evolution of the magma plumbing system at São Jorge Island, Azores

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Keywords: Azores hotspot, melt inclusions, volcanic hazard.

Recent unrest events on São Jorge Island (Azores) may signal impending volcanic eruptions, highlighting the urgent need to better understand the island's magma plumbing system. São Jorge lies on a thickened segment of oceanic crust, with the Moho estimated at approximately 15–18 km depth. Subaerial volcanic activity began around 1.8 million years ago, with the most recent eruption occurring in 1808 CE (Marzoli et al., 2024). The erupted magmas are primarily basaltic and basanitic in composition.

Olivine phenocrysts reveal evidence of open-system differentiation processes, including magma mixing and replenishment. Some olivine crystals display reverse zoning, with lower forsterite (Fo) content in the cores compared to their rims, while others contain distinctly different Fo values within the same sample. These zoning patterns are used to estimate the residence times of olivine phenocrysts before eruption, providing valuable insights for volcanic hazard assessment.

The exsolution of volcanic gases—particularly CO_2—from deep-seated magmas is likely a major trigger for eruptive activity. Olivine phenocrysts host commonly melt inclusions containing gas bubbles and exceptionally fluid inclusions. Raman microspectroscopy revealed that the fluid phase of these inclusions consists solely of CO_2, likely formed at high pressures. In the case of melt inclusions, CO_2 has a density of ca. 0.2 g/cm³, while the surrounding basaltic glass is hydrous and apparently devoid of carbon. In the case of the only analysed fluid inclusion, CO_2 has a density of ca. 0.6 g/cm³, indicating the coexistence of both liquid and vapour CO_2.

Collectively, these observations suggest that São Jorge's mafic magmas ascend rapidly from the deep crust or mantle to the surface.

Marzoli A. et al. (2024) - Time-dependent evolution and source heterogeneities of Ocean Island Basalts from a weak plume, São Jorge, Azores. J. Petrol., 65(12), https://doi.org/10.1093/petrology/egae122-

Logistic regression analysis for assessing indoor radon concentrations in geologically complex realms

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Keywords: indoor radon concentration, uranium, petrophysical properties.

We conducted a detailed analysis of dosimetric and γ-spectrometric data collected during several campaigns since 2019 in Western Liguria (Italy). This region is characterised by significant lithological variability and high indoor radon concentration (IRC) records, and, despite being relatively mountainous, it is densely populated. The results highlighted a close correlation between uranium concentration in rocks and IRC. Radon exceeding 200 Bq m^{-3} (the threshold imposed by the law since 2025) was predominantly recorded in dwellings overlying volcanic rocks with a uranium content larger than 4.5 mg kg^{-1}.

Despite the numerous measurements (about 100), representing the IRC spatial distribution and mapping the hazardous areas is challenging due to the uneven sampling. To overcome this issue, we first attempted to use the correlation between the concentration of uranium and IRC, measured on the same lithology. The presence of rocks with high uranium concentrations is associated with a significant increase in the potential risk of indoor radon concentration, emphasising the importance of considering local geology in radon hazard assessments. These results suggested that the uranium-radon correlation can be an effective baseline for studies on radon potential.

However, mapping the Geogenic Radon Potential (GRP) requires incorporating other geological information, as radon exhalation also depends on the petrophysical characteristics. To this end, we employed the logistic regression analysis, a statistical tool for inferring the probability of occurrence of a binary variable. With this approach, we calculated the probability for indoor radon concentration, assumed as the binary variable, to exceed 200 Bq m^{-3} ($^{IRC}200$). We considered uranium spectrometric measurements within a 300 m radius of the dwellings where indoor radon concentration was recorded. Fifty IRC and uranium data pairs over the same lithologies were selected to calibrate the regression. Besides rock uranium concentration, we combined the binary variable with a set of geological explanatory variables, i.e. petrophysical properties that can control radon exhalation. Including petrophysical parameters significantly enhanced the model's quality compared to a mere correlation between IRC and uranium concentration.

Finally, based on the logistic regression model, we mapped the GRP by interpolating probability values for $^{IRC}200$ calculated at more than 800 sites of the γ-spectrometry survey, i.e. even where no IRC record was available. Excluding the IRC records used for setting up the logistic model, a comparison with the observed values of indoor radon shows that most monitored dwellings (75%) indeed exceed the 200 Bq m^{-3} threshold in the areas with higher geogenic radon potential. This suggests that our approach can provide realistic estimates of indoor radon hazard.

Understanding channel dynamics in responses to high-magnitude floods: Insights for integrated hazard assessment and mapping

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Keywords: extreme events, channel widening, debris floods.

In recent decades, the frequency of high-magnitude to extreme hydrological events has substantially increased across many regions of the globe, including Italy. It is well established that such events can trigger geomorphological dynamics capable of significantly altering the configuration of river channels and floodplains, with critical implications for flood hazard. These considerations are particularly relevant in mountainous and hilly areas, where channel dynamics (e.g., major widening) and sediment transport processes (e.g., debris floods) often play a dominant role in determining the overall flood hazard and risk. This contribution aims to provide an overview of the most relevant scientific advancements achieved at the international level concerning two main aspects: (i) the understanding of channel geomorphic dynamics in response to high-magnitude flood events, and (ii) the development of geomorphic tools aimed at delineating flood geomorphological hazards, particularly their spatial mapping.

In addition to hydraulic components (e.g., unit stream power), various geomorphological factors are crucial in driving channel changes during flood events. Several studies have analyzed the geomorphic response of rivers to extreme floods (e.g., Surian et al., 2016), identifying lateral confinement and sediment availability as key controls on channel widening. Recent investigations have shown that the type of sediment transport processes locally triggered during floods further influences channel response. Specifically, under comparable boundary conditions, river reaches impacted by debris floods exhibit greater widening than those affected by water flows with ordinary sediment transport (Brenna et al., 2023).

In highly dynamic systems, flood hazard is only partly associated with inundation processes. Channel dynamics often represent an equally—if not more—significant component of hazard in such contexts. The scientific knowledge outlined here has the potential to greatly enhance our ability to effectively delineate and map the hazard associated with extreme hydrological events. In this regard, geomorphological tools have already been developed (e.g., Event Dynamics Classification; Morphodynamic River Corridors; see Rinaldi et al., 2015). Recent applications have demonstrated both the effectiveness of these tools and their limitations, highlighting the need for continued research on these topics (Brenna et al., 2024). Currently, both in Italy and across Europe the use of such tools remains limited in favor of predominantly hydraulic approaches. Integrating these approaches into land use planning and river management strategies could substantially enhance their effectiveness by accounting for the dynamicity of fluvial systems. In particular, these tools allow for the inclusion of a wider range of natural processes that contribute to hazards and, potentially, to risks affecting people, communities, and infrastructures.

Brenna A. et al. (2023) - What drives major channel widening in mountain rivers during floods? The role of debris floods during a high-magnitude event. Geomorphology, 430, 108650, https://doi.org/10.1016/j.geomorph.2023.108650.

Brenna A. et al. (2024) - Assessing the effectiveness of "River Morphodynamic Corridors" for flood hazard mapping. Geomorphology, 467, 109460, https://doi.org/10.1016/j.geomorph.2024.109460.

Rinaldi M. et al. (2015) - A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology, 251, 122-136, https://doi.org/10.1016/j.geomorph.2015.05.010.

Surian N. et al. (2016) - Channel response to extreme floods: Insights on controlling factors from six mountain rivers in northern Apennines, Italy. Geomorphology, 272, 78-91, https://doi.org/10.1016/j.geomorph.2016.02.002.

Reconstruction of a 3D bedrock model in the urban area of Palermo through wells stratigraphy and active and passive seismic data

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Keywords: three-dimensional geological model, urban area, multidisciplinary approach.

A multidisciplinary approach was applied to reconstruct a three-dimensional model of the bedrock top surface within the urban area of the Palermo Plain, Sicily, Italy. In this sector, the Oligo-Miocene terrigeneneous deposits of the Numidia Flysch constitute the geological bedrock, and the area is characterized by a dense and extensive built environment that largely obscures its geological and geomorphological features. The performed study and analysis have enabled a more detailed characterization of the buried geological setting through geological and geophysical surveys.

More than 1000 borehole data were analyzed to create a coherent model of the bedrock surface. Subsequently, active seismic surveys were carried out to determine Vs parameters. The resulting shear velocities computed for the lithologies composing the subsurface were consistent with previous studies (Martorana et al., 2018; Cafiso et al., 2023). Furthermore, ambient noise data were acquired and analyzed using the HVSR method. H/V spectral ratio curves show a prominent peak in the 0.8–2.5 Hz frequency band corresponding to the interface between the Pleistocene deposits and the underlying Numidian Flysch. The H/V curve inversion, constrained by boreholes and Vs velocity, allowed us to estimate the depth of the Numidian Flysch at 54 new locations within the urban area, increasing the available dataset and the spatial resolution in under-sampled areas.

Two comprehensive maps were produced: one representing the thickness of the Quaternary deposits and another depicting the elevation of the Numidian Flysch. Furthermore, a three-dimensional model of the bedrock surface was developed to illustrate its morphological characteristics. These models have been compared with existing stratigraphic and tectonic data from previous studies and geological maps.

The overall morphology of the Numidian Flysch top surface in the whole studied area is represented as a synform structure. This structure is confined by antiform structures partly controlled by the contribution of wide-angle faults and transpressive fault systems (Avellone et al., 2010). The Numidian Flysch top surface also shows more depressed shapes, most likely created by the morphological conditions that subsequently constrained the development of the drainage system along a preferential SW–NE direction. Nowadays, these depressed sectors host the main river paths within the plain. Moreover, a general drop trend of the surface according to a NE–SW direction can be recognized; this can be associated with a wider SSW–NNE antiform structure, which influenced the late Quaternary structural evolution of the Palermo Mountains complex and their deposits (Agate et al., 2025).

Maps and models derived through this integrated approach hold potential for various scientific applications, including stratigraphic, paleoenvironmental, and paleomorphological reconstructions.

Agate M. et al. (2025) - Decoding Late Quaternary faulting through marine terraces and MIS 5.5 tilted tidal notches: Insights from central Mediterranean Sea (NW Sicily, Italy). Geomorphology, 472, 109587, https://doi.org/10.1016/j.geomorph.2024.109587.

Avellone G. et al. (2010) - Interference between shallow and deep-seated structures in the Sicilian fold and thrust belt, Italy. J. Geol. Soc., 167, 109-126, https://doi.org/10.1144/0016–76492008–163.

Cafiso F. et al. (2023) - Joint interpretation of electrical and seismic data aimed at modelling the foundation soils of the Maredolce monumental complex in Palermo (Italy). Archaeol. Prospect., 30, 69-85, https://doi.org/10.1002/arp.1803.

Martorana R. et al. - A. Seismo-stratigraphic model of "La Bandita" area in the Palermo Plain (Sicily, Italy) through HVSR inversion constrained by stratigraphic data. Ital. J. Geosci., 137, 73-86, https://doi.org/10.3301/IJG.2017.18.

Guiding principles for the application of deep learning in Geosciences: common pitfalls and best practices

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Keywords: arificial intelligence, deep learning, computer vision

Artificial Intelligence is reshaping the way in which we make scientific research. Neural networks are powerful tools capable of learning complex patterns in data; they have been successfully applied in a wide range of fields, including medicine, engineering, physics, social sciences, and many others. Unfortunately, compared to other scientific fields, the application of artificial intelligence techniques in geosciences, albeit acquiring increasing traction, is still somehow lagging behind. In this context, some notable examples where neural networks are becoming more popular in geoscience are remote sensing, seismic signal analysis, mineralogy, and outcrop and image log analysis. Artificial intelligence tools and techniques are becoming increasingly accessible and easy to use, giving everyone the opportunity to integrate them into their usual workflow; on the other hand, this ease of use can make researchers underestimate potential pitfalls and mistakes that could limit, rather than improve, the quality of geological research in the era of artificial intelligence. Deep learning models, especially related to computer vision, have the power to speed up, strengthen, and standardize data extraction, manipulation, and consequent outcome prediction in a wide range of geological applications. On the other hand, deep learning models are known to be black-boxes, i.e., hardly explainable, or not explainable at all. For this reason, understanding the mechanisms that govern neural networks and applying proper techniques to make them work as intended is of paramount importance. We here present a review of the most common pitfalls and mistakes that can be made when applying deep learning to geological tasks. We will also go through the best practices to avoid unexpected model behavior, improve model performance, interpretability, and reliability. Finally, case studies where artificial intelligence was not applied correctly will be matched against successful applications of deep learning to geological problems, where artificial intelligence added value to the research, allowing analyses otherwise impossible or extremely time-consuming.

A multi-temporal SAR interferometry based procedure for detecting and interpreting 2016-2021 vertical ground deformation anomalies during the current phase of unrest at Campi Flegrei volcanic caldera, Italy

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Keywords: MT-InSAR, ground deformation, Campi Flegrei.

Active volcanic caldera often experiences significant ground deformation, characterized by uplift and subsidence, typically with a radial or elliptical pattern centered on the caldera. However, the detection of small second-order anomalies within the main deformation pattern can provide critical insight into impending eruptions and/or hazardous structural and volcano-tectonic features. In this study, we present a simple but novel method for detecting and interpreting second-order deformation anomalies at Campi Flegrei caldera by filtering the primary, radial deformation signal observed during volcanic unrest phases. For this purpose, we used a procedure based on the polynomial fit of vertical displacement data, assuming that they depend only on the distance from the deformation center. By subtracting the best fitting radial deformation from the observed vertical displacement, we generated an anomaly map that highlights sectors with unexpected deformation patterns. We applied the proposed procedure to analyze the ground deformation at the Campi Flegrei caldera (Italy) that occurred from 2016 to 2021, by using MT-InSAR data from Sentinel-1. Coeval GPS datasets were also used for cross-checking the obtained results.The results of this analysis show a pronounced NE-SW alignment that separates sectors with different uplift trends. It highlights a primary volcano-tectonic structure potentially linked to high seismic hazard.

The obtained results show that seismic structures that have not yet been fully activated can be recognized in the early stages of ground deformation from differential ground displacement anomalies, if appropriately filtered and analyzed. The spatial distribution of earthquakes occurring during 2022-2024 confirms the clustering of most of the largest-magnitude events around this structural feature, as detected from the analysis of deformations measured in 2015–2021, thus proving the robustness of the results obtained by such analyses.

This method, after further investigation, can provide a valuable tool for improving hazard assessment and understanding the structural dynamics of calderas during unrest phases, with implications for improving preparedness in densely populated volcanic regions.

Identification of recording stations in 1D site response conditions in Italy

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Keywords: microzonation, site effects.

The seismic microzonation studies aim to provide amplification factors that can be used at the municipal scale for urban planning. Estimates of amplification factors are based on the results of one-dimensional numerical analyses of local seismic response. In parallel, there are purely empirical methods for calculating the amplification factor based on the seismic waveforms available at recording stations. Comparing the results of numerical and empirical methods is not straightforward, as the starting assumptions of the two approaches can be very different and sometimes irreconcilable. In this study, we make a comparison in terms of transfer functions, trying to place the analysis under the same hypothesis. Specifically, we analyse the stations in the ITACA database that have a shear wave velocity profile Vs. With regard to empirical estimates, the approach of Brunelli et al. (2023) is followed, which is based on the analysis of residuals, calculated as the difference between the logarithm of observed and predicted ground motion model (GMM) intensity measurements. The systematic deviation of single-station observations from GMM predictions is called the site-to-site term (δS2S), which can be considered representative of site amplification at recording stations. One-dimensional numerical analyses are conducted with the STRATA code (Kottke & Rathje, 2009), initially assuming a linear elastic soil model. The assumption of linearity was introduced because empirical amplifications are mainly obtained from recordings of low-to-medium magnitude earthquakes in medium-to-long distance intervals (up to 200 km), which predominantly represent site effects in the linear elastic regime. To identify sites with an empirical 1D response, we calculated the Spearman correlation coefficient ρ to measure the similarity of the amplification curves obtained by numerical modelling following the approach used by Pilz & Cotton (2019). In total we identified 52 1D sites over 168 analysed stations. The approach used for this study could be used to validate the numerical analyses used for large-scale and municipal-scale microzonation studies with empirical data. It could be used as an intermediate analysis prior to comparison with amplification maps obtained from 1D analyses on typological Vs profiles.

Brunelli G. et al. (2023) - Estimation of the seismic microzonation amplification factors from the GMMs between-station residuals. GNGTS Conference 2023. Bologna, 7-9 Feb. 2023.

Kottke A.R., & Rathje E.M. (2009) - Technical manual for Strata (p. 103). Berkeley, California: Pacific Earthquake Engineering Research Center.

Pilz M. & Cotton F. (2019) - Does the one-dimensional assumption hold for site response analysis? A study of seismic site responses and implication for ground motion assessment using KiK-Net strong-motion data. Earthquake Spectra, 35(2), 883-905, https://doi.org/10.1193/050718EQS113M.

Using DInSAR to reveal ground deformation and crustal response to magma intrusion: the case of 2021 La Palma eruption

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Keywords: La Palma 2021, volcanic ground deformation, DInSAR technique.

The 2021 volcanic eruption of Cumbre Vieja, La Palma (Canary Islands) provided a unique opportunity to investigate the volcano-tectonic processes associated with magma migration and ground deformation. The precursory phase is considered to begin in 2017, characterized by the occurrence of several seismic swarms at depths of 20-30 km, culminating into the actual pre-eruptive phase started on 11 September 2021 and lasted until the onset of the eruption on 19 September. The pre-eruptive phase displays the main ground deformation related to a westward and upward magma migration prior to the eruption. The magma reaches the surface on 19 September at Tajogate volcano leading to the onset of the eruption, lasting 85 days up to 13 December. This study presents a detailed analysis of ground deformation associated with the pre-eruptive phase and partially the precursory phase, with the aim of investigating the mechanical response of the crust to magmatic intrusion. Multiple interferograms were generated, derived from Sentinel-1 Synthetic Aperture Radar (SAR) data, revealing significant surface deformation patterns temporally and spatially correlated with the magmatic migration that preceded the eruptive event. These deformation signals were extracted and processed using Differential Interferometric SAR (DInSAR) techniques within the ESA SNAP toolbox, allowing for the detection of surface displacements with high spatial resolution. Sentinel-1 data were processed with the open-source Python tool Snap2DQuake (Occhipinti et al., 2023). The observed ground deformation is interpreted as a direct manifestation of subsurface magmatic activity. This interpretation is supported not only by the morphology and evolution of the deformation fields but also by the distribution and the progression over time of seismicity during the pre-eruptive and eruptive phases. The spatial coincidence between seismic clusters and zones of maximum deformation (~ 15 cm), together with evidence reported in the existing literature concerning the case study, supports the hypothesis that the detected deformation results from the upward propagation of magma through the crust. By integrating seismic and geodetic data, this work aims to reconstruct the evolution of the magma intrusion and crustal response by identifying the primary patterns of upward dike propagation and assessing the temporal progression of induced deformation processes. The findings of this study will improve our interpretation of the 2021 La Palma eruption and deepen our understanding of how magma intrusions dive surface deformation and seismicity, contributing to more efficient hazard assessment and future monitoring strategies.

Occhipinti M. et al. (2023) - Implementing the European Space Agency's SentiNel Application Platform's Open-Source Python Module for Differential Synthetic Aperture Radar Interferometry Coseismic Ground Deformation from Sentinel-1 Data. Remote Sensing, 16, 48, https://doi.org/10.3390/rs16010048.

Assessing urbanization-induced land subsidence in Douala (Cameroon): A Deep Learning integration of remote sensing and soil data

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Keywords: land subsidence, neural network, urbanisation.

Rapidly growing coastal cities in the Gulf of Guinea, particularly low-lying areas like Douala, in Cameroon, face significant geo-environmental hazards, exposing the population, environment, and infrastructure to the impacts of sea-level rise, coastal erosion, and land subsidence. In Douala, rapid urban expansion has intensified environmental stress, contributing to land subsidence in vulnerable zones, with observed rates averaging -2.7 mm/year and reaching -17.6 mm/year in some areas over the period between 2018 to 2023. These phenomena are largely driven by land-use changes, mainly the urbanisation of croplands and wetlands. Despite this, the mechanisms driving land subsidence remain poorly understood, mainly due to limited data availability. This study aims to address this knowledge gap by applying a Deep Learning model to investigate the relationships between land-use change, shallow soil properties, building features, and subsidence patterns. The model combines land-use change data (1992-2022), geological soil data, urban built-up data from the Global Human Settlement Layer (1975-2020), and subsidence measurements from advanced InSAR. Empirical equations are implemented to quantify land subsidence and identify key spatial and temporal drivers of ground deformation, to support subsoil characterization, and to predict future subsidence patterns. The goals of this work are to develop the first integrated model of land subsidence associated with the urbanization of Douala and provide valuable insights for urban planning and geo-environmental risk mitigation in the region.

The Italian radon risk map: integrating geology, population exposure, and regulation in a national-scale assessment

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Keywords: Geogenic Radon Potential, machine-learning risk mapping, population-weighted Radon Priority Areas.

Italy's National Radon Action Plan, which executes the EU Basic Safety Standards (BSS 2013/59/Euratom) through Legislative Decree 101/2020, requires the development of two complementary cartographic products: (i) *Geogenic Radon Potential (GRP)* maps illustrating the geological hazard and (ii) *Radon Priority Areas (RPAs)* integrating hazard with population exposure indicators to guide remediation actions. However, a complete, geologically-based methodology to link the geological origin of radon to indoor risk had never been established on a national level (Benà et al., 2025). The work presents the Italian Radon Risk Map, a holistic approach that combines geological data, soil gas measurements, fault density, gamma radiation dose rate, and morphometry with census data on building types and resident populations. Over 30,000 soil-gas samples and 11 geogenic predictor maps were standardized on a 1 km grid and analyzed using supervised automated machine learning (Autogluon). The LightGBMLarge algorithm provided the best model, which outperformed 10 other algorithms (test RMSE 0.95; R^2 0.54). SHAP analysis shows that equivalent uranium, soil type, and fault density are the primary factors affecting GRP, emphasizing the significant influence of lithology and tectonics on radon availability. The calibrated model produces a six-class GRP raster with values from 5 to 245 kBq m^{-3}. Crystalline Alpine massifs, volcanic regions, and significant Apennine fault zones are categorized as "very-high" classes, while the Po Plain and foredeep basins are classified in the "very-low" range. The GRP was merged with census tracts to convert the *hazard* into *risk*. For each polygon, we calculated the likelihood that indoor radon concentrations exceed the Italian reference limit (300 Bq m^{-3}) and weighted that probability according to the population density. The resulting risk map shows contiguous High-Risk/High-Dose clusters in central Apennine municipalities and volcanic areas and numerous densely built coastal areas with Low-to-Medium risk, because of the low geogenic contribution.

Our results demonstrate that: i) geology serves as the only nationwide, spatially consistent proxy for radon sources and migration; ii) including tectonically-enhanced permeability (fault proxies) enhances predictive accuracy by over 10% (Benà et al., 2022); iii) population-weighted risk identifies hotspots undetectable by criteria based only on the percentage of houses over 300 Bq m^{-3} (15% rule) (Benà et al., 2024). A geology-based RPA approach is proposed: GRP acts as a mandatory first-order filter, later modulated by building vulnerability and demographics. This approach bridges the gap between geoscientific evidence and public health regulations, providing planners with a tool for sizing mitigation systems and for prioritizing mitigation funds, environmental impact assessments (VAS), building codes (PRG) and building permits (PSC) to reduce both individual and collective radon risk.

Benà E. et al. (2022) - Evaluation of tectonically enhanced radon in fault zones by quantification of the radon activity index. Sci. Rep, 12, 21586, https://doi.org/10.1038/s41598-022-26124-y.

Benà E. et al. (2024) - A new perspective in radon risk assessment: mapping the geological hazard as a first step to define the collective radon risk exposure. Sci. Total Environ., 912, 169569, https://doi.org/10.1016/j.scitotenv.2023.169569.

Benà E. et al. (2025) - From collective to individual radon risk exposure: An insight into the current European regulation. Env. Int., 196, 1-12, ISSN: 1873-6750, https://doi.org/10.1016/j.envint.2025.109264.

Unmasking the subsurface: Sensitivity insights from multi-coil vs multi-frequency FDEM for UXO detection

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Keywords: UXO, FDEM, sensitivity analysis.

A factor that contributed to the radical change of the urban geomorphological landscape until nowadays was war. An uneasy inheritance we have to deal with is Unexploded Ordnance (UXO), which are spread all over the country. To that extent, Electomagnetic (EM) Induction suits well for their detection, other than have many environmental applications, as non-invasive geophysical method (Boaga, 2017). We can distinguish between two families of FDEM instruments: multi-Coil and multi-Frequency. Their intrinsic properties make them differ in terms of manageability and depth of investigation, which are in trade off. The location of this study is a test site in Cittadella (PD) owned by the company "Geoside Geofisica s.r.l.", involving eleven buried metallic tubes, of different sizes, at different depths, that simulate the presence of UXOs. Firstly, we carried out three ERT measurements across the area to obtain a consistent resistivity model of the subsoil. Secondly, we test the effectiveness of three electro-magnetometers, one multi-Frequency (GEM-2) and two multi-Coil (CMD-Explorer, CMD-MiniExplorer) over the buried targets. In parallel, to define which instrument is more suited to detect them, we conduce a Sensitivity Analysis to both parameters of the subsurface, Electrical Conductivity (EC) and Magnetic Permeability (MP). It is carried out with two different software, EMagPy (McLachlan et al., 2021) and FDEMtools (Deidda et al., 2023), and it clearly reveals the main differences between multi-Coil and multi-Frequency instruments. Within the range of resistivity present in the site, both EC and MP sensitivity curves resulting from all six frequencies of the GEM-2 (425 - 92775 Hz) overlap showing, in the first case, a common maximum value at about 0.5m depth and, in the second case, a negative pick at about 0.2m depth and then a positive pick at almost 1m depth. Differently, concerning CMD-Explorer and CMD-MiniExplorer, EC and MP sensitivity curves show a different evolution through the depth. In all cases, MP sensitivity curves reach relative high values at larger depth compared to EC ones. More, sensitivity analysis shows that by increasing the height of the coils, EC sensitivity curves undergo a vertical shift, while MP ones do not show the same behave. In conclusion, sensitivity analysis shows evidence that different coils spacing is a more relevant factor rather than multi frequency for a better sensitivity evolution within the depth. Moreover, it suggests that the component of the signal related to MP is the best option for the detection of UXO. Finally, GEM-2 may be a valid solution for the detection of buried metallic objects and it is easy to handle, but it is not suited for a site characterisation if not in very conductive environments. Otherwise, CMD-Explorer and CMD-MiniExplorer find good application in both scenarios, but the former is not easy to handle, and the latter is designed to investigate the shallowest portion of the subsurface.

Boaga J. (2017) - The use of FDEM in hydrogeophysics: A review. J. Appl. Geophys., 139, 36-46, http://dx.doi.org/10.1016/j.jappgeo.2017.02.011.

Deidda G.P. et al. (2023) - Forward Electromagnetic Induction Modelling in a Multilayered Half-Space: An Open-Source Software Tool, Remote Sens., 15, 1772, https://doi.org/10.3390/rs15071772.

McLachlan P. et al. (2021) - EMagPy: Open-source standalone software for processing, forward modeling and inversion of electromagnetic induction data, Comput. Geosci., 146, 104561, https://doi.org/10.1016/j.cageo.2020.104561.

Potential fields insights into sinkhole evolution: Case studies from the metropolitan area of Rome

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Keywords: sinkhole, magnetic prospecting, subsurface characterization.

Geophysical prospecting techniques rely on detecting contrasts in the physical properties of subsurface materials, which generate measurable anomalies when investigated using passive or active sensing methods. In the context of sinkhole investigations, these contrasts typically arise from variations in density, electrical resistivity, seismic velocity, or magnetic susceptibility—often associated with voids, unconsolidated deposits, or altered bedrock. By employing active techniques such as seismic or electrical resistivity tomography, or passive methods like gravimetric and magnetic surveys, geophysics enables the delineation of collapsed or potentially collapsing zones in terms of extent and geometry. These non-invasive approaches are essential tools for subsurface characterization, contributing to risk assessment and early warning in areas affected by ground instability, whether of natural or anthropogenic origin. In this work, we present significant results obtained through potential field methods, with particular emphasis on magnetic surveys. Magnetic measurements were carried out at two sites representing different evolutionary stages of sinkhole development within the Metropolitan Area of Rome. The first site is an incipient sinkhole in the Acque Albule basin, a sinkhole area located approximately 25 km east of Rome. The second site is the Lago Puzzo, which we interpret as an ancient but still active sinkhole, situated near the village of Capena, about 30 km northeast of the city. Our findings demonstrate that magnetic prospecting provides valuable information on the geometry of buried sinkholes and highlights the associated fracturing patterns. While the origin of the magnetic sources remains under debate, we propose a likely interpretation based on the distinctive hydrogeological, structural, and volcanic settings shared by both study areas.

Integrating field tests, lab determinations and geospatial modelling for regional engineering geological classification of sub-surface bedrock masses: the new "carta litotecnica" of Tuscany (Italy)

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Keywords: engineering geological mapping, geological units, bedrock masses.

Public administrations involved in natural hazard assessment and land-use planning rely on geo-thematic datasets (e.g., geology, geomorphology, lithology, hydrogeology) as essential tools to support decision-making. Among these, lithological and engineering geological databases — where geological units are grouped into litho-technical units mainly based on lithology — are widely used. Occasionally, these databases may also incorporate available field and laboratory investigations data, such as boreholes, penetrometric tests, or geophysical surveys. However, they often suffer from a degree of subjectivity, as lithological groupings and expected mechanical properties are typically expert-based and supported by few quantitative data.

We present the new engineering geological database for the Tuscany Region, developed by integrating the official 1:10,000 geological map (DB Geologico Regionale) with a large set of new lithological and engineering geological mesoscale data collected from outcropping bedrock units. The adopted methodology combines field tests — namely, Schmidt hammer rebound and pocket penetrometer tests — with laboratory analyses, such as Slake Durability Test (SDT) and unit weight measurements. This information allowed us to obtain a regional-scale novel dataset with high repeatability. Each survey site was classified according to a new nomenclature, coded as XXvv[y]_[Z], derived from: (i) a primary engineering geological parameter (XX) based on either macroscopic evaluations of consistency/cementation or rock mass quality index (RQI), as estimated via the Schmidt hammer and SDT results; (ii) a lithological parameter (vv) derived from outcrop structural features and field observations; (iii) an engineering geological parameter [y] linked to the weakest lithology of the outcropping unit (again based on the SDT); and (iv) a parameter [Z] based on RQI values. We stored classification results in a point-topology GIS dataset that allowed us to perform, in turn, classification of geological formations by means of geostatistical and clustering techniques, hence resulting in a new polygon-based thematic map.

The final database, named BD_Litec, includes the engineering geological classification of more than 450 geological units across Tuscany (ca. 17,500 km²) and is available online through the Regione Toscana GEOscopio web portal. The implemented approach offers a repeatable framework for engineering geological mapping of near-surface bedrock units at regional scale, providing a more refined and quantitative classification than existing litho-technical maps, representing a significant advancement in engineering geological mapping. Moreover, the BD_Litec allows to preliminary analyse engineering geological conditions for several applications such as: slope stability, spatial planning and civil engineering plans.

Investigating the interaction between mud volcanoes activity and seismicity: perspectives from the continuous multiparametric monitoring of Salse di Nirano (Italy)

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Keywords: crustal fluids, earthquakes, multidisciplinary approach.

Mud volcanoes are found worldwide but are predominantly located in accretionary complexes within compressional tectonic settings along subduction zones, areas often marked by high seismic activity (Dimitrov, 2002). The Regional Natural Reserve of Salse di Nirano (Fiorano Modenese, Italy) hosts one of the largest mud volcano fields of Europe. Placed near the Apennine margin, it emits fluids mainly consisting of clay mud, saline water and hydrocarbons (liquid and gas). Gas emissions are primarily composed of methane (> 98%), with minor contributions from carbon dioxide, nitrogen, and other hydrocarbons (e.g., Etiope et al., 2007). The area is positioned upon an anticline structure of the NE-verging fold-and-thrust Apennine belt. Mud volcanoes lie at the bottom of a caldera-like depression presumably formed because of mud diapir top collapse following severe fluid emission. Faults and fractures allow fluids migration to the surface. In particular, two main fault and fracture systems can be distinguished, one NW-SE oriented and the other SW-NE/ENE-WSW oriented (e.g., Bonini, 2008).

The site is thus well suited for analysing the relationship between geofluids and seismicity, owing to the close connection between mud volcanoes emissions and the local tectonic structure. For this purpose, two distinct mud pools were selected for the continuous monitoring of mud level/density, temperature and electrical conductivity. In addition, a permanent station measuring CO_2 flux diffused by the soil was installed at the edge of the mud volcanoes field, where higher CO_2 fluxes were detected (Ferrari et al., 2024). Additionally, a meteorological station and a velocimeter were installed to monitor the atmospheric parameters and the seismic activity of the area, respectively.

To date, about two years of multiparametric data has been continuously recorded. Periodic oscillations were identified, with some anomalous variations of mud level, temperature, electrical conductivity and CO_2 soil flux that have been compared with environmental data (meteorological and soil-related) and seismicity. Notably, synchronous changes in mud pools electrical conductivity and soil CO_2 fluxes were detected in relation to two distinct seismic swarms occurred in February and August 2024. In addition, differences in the behaviour of the two mud pools were also observed throughout all the time-series and presumably point to extremely local conditions influencing the common feeding system. All these observations highlight the efficiency of the presented continuous multiparametric monitoring system in inferring new insights on mud volcano crustal fluids dynamics.

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3D seismostratigraphic fine-scale subsoil model of L'Aquila (central Italy) for evaluating the local seismic effects

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Keywords: 3D geological-geophysical subsoil model, Petrel software, L'Aquila.

For L'Aquila, a regional administrative town, which was strongly affected by the well-known April 6, 2009 Mw 6.3 near-source earthquake (Chiarabba et al., 2009), we propose a detailed database integrating geological, geophysical, geotechnical, and borehole data. It serves as input for setting up the detailed 3D seismostratigraphic subsoil model for evaluating the local seismic effects of L'Aquila about 60 km^2-wide area. The database was constructed with QGIS (ver. 3.36) software and a first version of the 3D geological-geophysical model by using Petrel software by SchlumbergerTM, where a data-supported minimum convergent interpolation method was applied (Livani et al., 2022).

More than 1300 shallow boreholes, about 50 deep boreholes, several seismic reflection profiles and gravimetric maps were loaded to create a complete database constraining the geo-lithological characteristics of the studied area. To delimit the outcropping boundaries between the different Plio-Quaternary alluvial-slope units and the Meso-Cenozoic top-bedrock surface, we utilized the map by Nocentini et al. (2017). Moreover, we reorganized the various geological formations reported by Nocentini et al. (2017) into seven classes to perform a classification based on the geophysical properties (Macerola et al., 2019). The approach presented in this study integrates various analyses, enabling the construction at fine scale of a realistic 3D subsoil model on the best available data. The novel feature for L'Aquila area is not merely the result of interpolation but is based on data-supported reconstruction.

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Testing the capability of satellite-based InSAR data to assess differential subsidence risk in the Emilia-Romagna region, Italy

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Keywords: land subsidence, risk assessment, In-SAR data.

Land subsidence—defined as the loss of land elevation of the Earth's surface due to natural and anthropogenic processes at depth—is affecting many parts of the world and has various impacts with geological, geomorphological, environmental, hydrogeological, and economic consequences. In particular, urban areas located in subsidence-prone regions may experience damage, as differential settlement can compromise the integrity of buildings and infrastructures. Risk assessment tools serve as a guide for preventing future damage and supporting informed urban planning decisions in the context of resilience.

This study presents a methodology to assess differential subsidence risk in urban areas of the Emilia-Romagna Region (Italy), which is historically affected by land subsidence, with recorded rates up to 7 cm/year since the 1950s. Utilizing open-source ground displacement data collected between 2018 and 2022, from the European Ground Motion Service (EGMS), which is part of the Copernicus Land Monitoring Service (CLMS), we assessed hazard levels associated with differential settlement. Exposure and vulnerability were evaluated using the World Settlement Footprint Evolution (WSF), Global Human Settlement Layer (GHSL), along with a regional building footprint dataset provided by the Emilia-Romagna region. The risk components were integrated into a risk matrix to distinguish risk levels ranging from low (R1) to very high (R4). The outcomes demonstrate that the high and very high levels of risk (R3 and R4) were identified across almost 1.8 km^2 built-up areas of the region. Moreover, the highest risk levels are mostly limited to the Ravenna and Bologna provinces. This approach gives insights into the pros and cons of the use of these datasets to guide the informed EGMS user uptake for risk assessment. Overall, it provides a more accessible perspective on how differential subsidence could affect urban regions.

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Effects on local seismic response due to underground caves though a geophysical-validated numerical modelling

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Keywords: parametric analysis, numerical modelling, local seismic response.

In Mediterranean areas, many countries have several natural and anthropic underground caves, which have been used for different purposes over time and they can represent a potential geo-hazard for both buildings and infrastructures, especially in the historical centers hosted in seismically active areas (Fabozzi et al., 2024; Faraone et al., 2023).

The main source of cavity-related risk is due to two different phenomena: i) stress induced by seismic shaking can exceed the rock strength of around the caves, causing a vault collapse; ii) seismic waves propagating inside the caves can be modified in terms of frequency, amplitude and duration, influencing the local seismic response with respect to a free field bedrock (Fabozzi et al., 2024). Nowadays, the impact of underground caves and the prediction of their related effect on seismic motion are generally not taken into account for Seismic Microzonazion (SM) studies.

In the literature, a 2D model is proposed to study the propagation of shear seismic waves caused by a single arch-shaped cave in homogeneous rock, considering their size and depth (Lancioni et al., 2016). Furthermore, Faraone et al. (2023) performed a local seismic response study using 2D linear numerical analysis on urban cavities, considering different soil shear wave velocities (Vs), sizes, depths, and lining conditions.

This study proposes an improvement in understanding the mechanisms of interaction between surface seismic waves and natural caves under free-field conditions. It also seeks to categorize local seismic response based on their physical and mechanical characteristics. A statistical study performed on a dataset of sinkholes inventoried in the Maltese Archipelago allow to identify the relevant morphometric parameters: predominant geometries, size classes, depths and the lithologies. Specifically obtained geological sections reinstituted the average thicknesses of the geological units have been obtained. The combination of all these variables allowed to setup a parametric analysis via numerical modelling, based on the most representative combinations.

The parametric analysis includes a two-dimensional numerical modeling (2D) under Linear Elastic conditions through the finite difference code FLAC 2D (Itasca Consulting Group). The same methodology is applied to "validating cases (VC)": sites where geophysics data are available. These sites are Ghar il-Latnjia and Ghar il-Kbir Caves in Malta and Battifratta and Grotta Scura Caves in Italy.

Finally, once the simulations have been validated, they will be applied to a "demonstrating case (DC)", where no geophysical data are available. In this case, the DC selected is the Tal-Mixta Cave in Gozo.

The challenge of this study is to develop seismic intensification charts in order to standardize the seismic response of natural cavities under free-field conditions, considering different geometries, depths, and size classes.

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Utilizing multiparametric likelihood for seismic hazard definition: SHAKER as a ground motion selection tool

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Keywords: seismic local hazard, spectral compatibility, consistency analysis.

Accurate selection of ground motion records is fundamental for reliable seismic hazard assessments and engineering analyses. Traditional approaches often focus on spectral compatibility alone, potentially neglecting key parameters that critically influence structural response. To address this, we present SHAKER (Grelle et al., 2023), an open-source Python-based tool designed to select input ground motions using a multiparametric likelihood framework. This approach integrates spectral matching with physical consistency in terms of energy content, frequency characteristics, and duration, thereby enhancing the representativeness of selected records.

SHAKER evaluates a suite of seismic parameters: PGA, PGV, Arias intensity, significant duration, balancing spectral shape, energy distribution, and time-domain features. Selection is conditioned within realistic magnitude, distance scenarios, ensuring that chosen events reflect the seismic hazard level of interest. Additional constraints, such as scaling factors and PGA thresholds, limit excessive scaling and preserve signal realism. A key strength lies in the scaling to spectral equalization of Housner intensity concerning the target hazard spectrum within an interval relevant to engineering applications. This imposed condition increases the avoidance of over-representation in specific spectral intervals promoting a balanced spectral assortment. Furthermore, the hazard target spectrum with different damping ratios can be considered.

This process mitigates the limitations of conventional selection methods, which may yield records that are spectrally compatible but dynamically inconsistent. By enforcing both spectral and energetic coherence, SHAKER provides more realistic ground motion inputs capable of exciting structures with varying mass-stiffness properties and damping ratios. This approach is particularly effective for the analysis of slope instabilities (Grelle et. al., 2025; Grelle & Guadagno, 2013), as it accommodates the wide range of landslide typologies, from deep-seated failures in soft soils to the sudden collapse of limited rock masses, ensuring that selected motions appropriately reflect the diverse dynamic responses involved.

The efficacy of the tool was validated through its application to the Mw 6.0 Amatrice earthquake (2016) (Grelle et al., 2020). In this retrospective analysis, SHAKER identified ground motions that closely reproduced the seismic characteristics observed during the event. The resulting selections matched not only the target spectrum but also the temporal and energetic features driving the actual damage patterns. This confirms SHAKER's ability to capture the complex interplay of ground motion parameters in real scenarios.

In conclusion, SHAKER offers a robust, physically consistent, and reproducible method for selecting ground motion records. Its multiparametric likelihood design enables tailored hazard representations and supports advanced seismic risk evaluations, contributing to safer, more resilient structural designs in seismically active regions.

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Semantic segmentation of UAV imagery for automated mapping of fresh mud flows in Sicilian mud volcanoes

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Keywords: semantic segmentation, UAV remote sensing, mud volcano monitoring.

In Italy, over 80 sites of mud volcanism have been identified, with some of the most active and geologically significant located in Sicily. These sites are known for their scientific relevance and associated hazards such as sediment liquefaction and sudden mud eruptions (Mazzini & Etiope, 2021). To support hazard assessment, this study develops a semantic segmentation pipeline for UAV-acquired imagery to distinguish fresh mud extrusions from inactive or crusted zones. Semantic segmentation assigns a class label to each pixel, enabling detailed surface classification in complex environments. It is widely used in environmental monitoring, especially for risk assessment and terrain analysis (Alam et al., 2021). Deep learning methods have shown strong performance in UAV-based visual tasks, particularly under varying conditions of scale, angle, and terrain complexity (Tang et al., 2024). A manually annotated dataset of 1,274 high-resolution UAV images was compiled from INGV archive surveys at the three sites of Santa Barbara, Paternò, and Aragona, and augmented via horizontal flipping, brightness/contrast variation, and Gaussian noise to improve generalization. Six segmentation architectures (DeepLabV3, U-Net, FPN, LinkNet, PAN, PSPNet) were trained using varying batch sizes (8, 16, 32), optimizers (Adam, AdamW, SGD), and learning rates (1e−4, 5e−4, 1e−3). Training was conducted for up to 100 epochs with early stopping (patience = 20), using a composite loss function combining binary cross-entropy and Dice loss, and evaluated via mean Intersection over Union (mIoU). The best-performing model in each configuration was checkpointed upon improvement in validation IoU. AdamW consistently led to the fastest convergence (within approximately 50 epochs) and highest test IoU scores. FPN achieved the top score of 0.9815, followed by U-Net (0.9810) and DeepLabV3 (0.9805); LinkNet, PAN, and PSPNet scored below 0.98. Optimal results occurred with a learning rate of 1e−3 and batch size of 8. SGD-based models lagged by 2–3% and typically required full training due to slower convergence of loss functions. Given the high contrast between fresh mud and surrounding terrain, and the binary nature of the task, high IoU scores across models are expected. Fresh mud typically forms homogeneous, smooth, dark-toned regions, clearly distinguishable from cracked or vegetated surfaces. The top-down view avoids distortion, and high resolution captures fine edge details, reducing ambiguity. These conditions simplify segmentation, allowing most architectures to converge quickly and perform near the task's upper bound. These results offer the first quantitative benchmark for mud volcano imagery, showing that off-the-shelf segmentation models enable near pixel-perfect mapping for automatic detection and long-term monitoring in a domain still underexplored by computer vision.

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Hydroseismograms from pressure devices in deep borehole within the Gran Sasso aquifer (central Italy) in earthquake hydrogeology studies

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Keywords: pore pressure monitoring, seismic monitoring, hydroseismogram.

This study explores, for the case study of the Gran Sasso Aquifer (GSA), the potential of high-frequency pore pressure monitoring (hydroseismograms) for enhancing the understanding of earthquake physics. This research has been developed within the Euratom funded ArtEmis Project and the HPC, Big Data and Quantum Computing - PNRR Project, funded by the European Union - Next Generation EU. Hydroseismograms, derived from a hydraulic pressure device (HPD) within deep, horizontal wells intersecting a major fault system inside the GSA, are compared with seismic data from the proximate seismic station, named GIGS, to gauge the HPD's earthquake detection capabilities. This distinctive setup, coupled with the HPD's 20 Hz data acquisition, provides a sensitive means for tracking both seismic events and pore pressure variations. The GSA's fractured-karst geology and its placement within a seismically active zone in Italy, alongside the Italian Institute of Nuclear Physics (INFN) underground lab (UL), establish an optimal setting for examining interactions between deep, saturated aquifers and earthquakes.

Based on monitoring data from May 1, 2015, to December 31, 2023 (continuous), the primary objectives were:

- Evaluating our HPD's performance in seismic detection and monitoring,
- Comparing the HPD's sensitivity against the GIGS seismic station,
- Comparing the HPD's sensitivity to comparable instruments in existing literature,
- To elucidate the different behavior of our HPD relative to analogous devices used by other researchers.

Here, HPD sensitivity is evaluated against the GIGS station. Therefore, sensitivity is here intended as conditional probability that a seismic event is detected by the HPD, given that it has already been detected by the GIGS. A statistical inferential method was employed, comparing HPD-detected events with GIGS-recorded events (1068) across varying magnitudes and distances. Key findings (Isaya et al., 2025):

- Mainly for far events, the identified detection threshold notably surpasses the "hard" detection limit for typical aquifers reported by Montgomery & Manga (2003), below which they observed no detections in a large dataset.
- It appears more effective than similar pore pressure sensors, even for deep events, although this analysis focused on far events due to a scarcity of near, deep earthquakes.
- Overall, our HPD exhibits substantially different sensitivity characteristics compared to analogous instruments documented in the literature.

These findings warrant further research into the not yet fully understood physics of hydraulic response to seismic events. This work highlights the potential of HPDs installed in deep boreholes for seismic monitoring and understanding the complex interplay between hydrological processes and seismic activity. Ongoing HPD monitoring will further investigate their role as a valuable tool for future seismic investigations and contribute to advancing earthquake science.

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Radon monitoring in groundwater within the framework of the Euratom funded ArtEmis project: selection of sites in the Abruzzo aquifers (central Italy)

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Keywords: hydrosensitive to seismicity sites, radon monitoring, carbonate aquifer.

Radon is progressively emerging as an effective geogas tracer for geodynamic processes and a potential earthquake precursor (Joint Research Centre of European Commission, 2024; Stoulos et al., 2024, and references therein). The Euratom-funded ArtEmis project (http://www.artemisproject.eu/) plans to build a European network of low-cost, multiparametric sensors to monitor radon concentrations in groundwater with high spatial and temporal resolution, on three key areas in Europe. One of these is the Abruzzo region, in central Italy, which has been selected for its significant seismicity and peculiar seismotectonic and hydrogeological features. One of the ArtEmis objectives is to address the long-standing question of whether radon monitoring in groundwater can provide reliable short-term precursors for destructive earthquakes (JRC EU). Moreover, ArtEmis aims to establish an optimized model for environmental and natural hazard monitoring, leveraging low-cost multisensor networks, data processing powered by machine and deep learning algorithms, and active municipalities engagement to improve scientific dissemination and population preparedness.

Consequently, particular attention in ArtEmis has been given to the selection of radon monitoring sites in the monitored areas. As radon concentrations in groundwater are believed to be less susceptible to the shallow phenomena than measurements in soil gas, radon monitoring will be carried out only within carefully selected high-discharge springs. Site selection prioritized hydrosensitive to seismicity locations, considering source rock properties, hydrogeological and seismotectonic settings and seismic activity, viewed as main factors affecting radon release.

This work is focused on the selection process of the hydrosensitive to seismicity sites in Abruzzo, where sensors will be installed. Source rock properties, hydrogeological conditions, seismotectonic setting, and seismic activity were all considered in site selection due to their influence on radon release into groundwater. Sites were chosen within carbonate aquifers, intermontane plains, and spa areas due to the presence of major seismogenic faults, high-discharge springs and the noticeable upwelling of geogas such as CO_2 as potential carrier for radon.

The chosen sites are primarily high-discharge springs. These springs tap into a significant volume of carbonate aquifer intersected by seismogenic faults, reflecting deep processes, such as the radon upwelling, unaffected by surface ones or significant seasonal variations in the water cycle.

Radon monitoring has started in Abruzzo, currently deploying three sensor prototypes within the Gran Sasso carbonate aquifer and the Sulmona plain.

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Volcanic vortex rings and puffing degassing

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Keywords: volcanic vortex rings, puffing degassing, volcanic conduit dynamics.

Active volcanic degassing often includes puffing activity—i.e., the repeated emission of discrete gas volumes, with inter-event duration of few seconds. Puffing may give rise to Volcanic Vortex Rings (VVRs) that are toroidal vortices of volcanic gases. Reports of VVRs date back to 1700s and they have been observed at different volcanoes, including Vesuvius, Mt. Etna, Stromboli, Pacaya, Yasur, and Whakaari. Despite their striking appearance, VVRs remain poorly characterized in the volcanological literature. This study presents a first attempt to characterize systematically VVRs, to better constrain the mechanisms of magma degassing in the shallow plumbing system. Observations were carried out at Bocca Nuova (Mt. Etna, Italy) during summer 2023, using thermal cameras that recorded continuously for 10 days. Video data were analysed with ImageJ to track VVRs' evolution and motion with time. We propose the Volcanic Vortex Ring Index (VVRI) to classify VVRs according to their physical features: shape, diameter, height from the emitting vent, residence time in air, vertical rise velocity, diameter expansion rate. The VVRI ranges from 1 (irregular, short-lived rings) to 4 (well-defined, stable rings). To overcome the time-consuming and subjective nature of manual analysis, we developed a MATLAB script that analyses pixel colour intensity from the thermal videos. This automated approach produces kymographs that show VVRs' evolution with time. VVRs typically rise and expand rapidly during their initial phase, then ascend with nearly constant diameter until they dissipate by mixing with surrounding air. VVRI-4 rings can exceed 30 m in diameter and 70 m in height, lasting tens of seconds with initial vertical rise velocities up to 22 m/s. VVRI-1 rings reach up to 20 m in diameter and 30 m in height, persist for less than ten seconds, and rise at initial vertical velocities up to 10 m/s. We also investigated the minimum conditions required for VVRs formation at volcanic vents. Vortex rings were experimentally reproduced using a device, consisting of a cylinder, a piston and a spring. We simulated the bursting of gas slugs of varying sizes, with different piston accelerations. First results offer a valuable insight into the conduit dynamics and the shallow degassing processes. Characterizing VVRs may provide insights into vent conditions during explosive activity and active degassing of volcanoes.

Investigating the evolution of Active Deformation Areas (ADAs) in Veneto-Friulian plain by integrating D-InSaR approach and ADAFinder tool

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Keywords: multi-temporal D-InSAR, EGMS, ADA.

Coastal alluvial plains with unconsolidated deposits are vulnerable to land subsidence, posing risks to infrastructure and drainage. The Venetian–Friulian coastal plain in N-E Italy exemplifies this, where sediment compaction and human activities have led to ground deformation. This study analyzes 30 years of land subsidence in the Venetian–Friulian plain, focusing on municipalities such as Portogruaro, San Stino di Livenza, Eraclea and Caorle. The dataset includes multi-sensor SAR data from 1992 to 2021, encompassing various satellite sources (ERS, Envisat, Cosmo SkyMed, Sentinel-1 and EGMS). The research utilizes InSAR data and ADAFinder tool to investigate subsidence patterns and to identify Active Deformation Areas (ADAs). Multi-temporal optical satellites images have been used to evaluate the progression of urbanization in the study area, to evaluate the influence of compaction of sediments in the subsidence phenomena. Findings indicate that buildings constructed before the early 1990s resulted in significant ground deformation in the late 19th Century due to consolidation of sediments but have shown signs of stabilization in the last two decades as expected in a consolidation process. This study highlights the importance of long-term, multi-sensor D-InSAR analysis combined with ADAFinder for effectively identifying Active Deformation Areas. The research provides critical insights into ongoing geohazard surveillance, increasingly relevant to urban development and planning. By integrating these findings, urban planners and policymakers can develop strategies that address immediate risks while anticipating potential hazards in geologically unstable sedimentary regions.

Preliminary numerical analyses of 3D seismic site response in the Norcia sedimentary basin (Central Italy)

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Keywords: numerical simulations, numerical analysis, earthquakes.

The historic town of Norcia (Nursia), which has been settled within the basin since the fifth Century A.D., was recently hit by the M6.5 earthquakes that occurred on October 30th, 2016. This extensional intermountain basin, measuring about 8x4 km, is filled with Quaternary fluvio-lacustrine sediments.

As part of the INGV project PD-GEMME, 3D physics-based numerical simulations are carried through the spectral element code SPEED (http://speed.mox.polimi.it/), with the aim of investigating seismic wave propagation features within the Norcia sedimentary basin (central Apennines, Italy). In particular, we focus on i) a sensitivity numerical analysis based on a preliminary simplified geological-geophysical model of the area; ii) the definition of a numerical model suitable to reproduce the basin seismic response, including non-linear effects, in the high frequency range. The first goal is achieved using a homogeneous description of the sedimentary basin, whose 3D geometry is derived from Di Giulio et al. (2020). Seismic input is given by vertical-incident Ricker-wavelets with different frequencies (0.5, 1 and 2 Hz), in order to assess the accuracy of the numerical simulation in different frequency ranges and for different boundary conditions. To fulfill the second goal, and therefore to improve the knowledge on the lateral and vertical variation of velocities within the basin, a series of new site investigations have been carried out including: 5 passive seismic arrays, 4 MASW investigations and a stratigraphic borehole with undisturbed sampling, where a down-hole test is performed. The results of these investigations are combined with the available literature information, to develop a numerical model suitable to simulate ground motion with a frequency content reliable at least up to 5 Hz at each of the stations of the 3H-2009 network (Bindi et al., 2011) as well as of the other permanent and temporary networks installed in the study area.

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High-resolution geophysical investigation in the metropolitan area of Milan (Italy) and implications for site-dependent seismic hazard

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Keywords: seismic active, long period analysis, seismic hazard.

The work shows the results of a detailed urban-scale seismo-stratigraphic model for Milan metropolitan area (Northern Italy), obtained from the analyses of existing geological data, ambient noise measurements, passive ambient-vibration arrays and newly acquired active seismic investigations. The study is a deepening of a previous characterization of the spatial variability and influence of seismic site response of the shallow to deep (~1.5 km) alluvial deposits for the Milan urban area (Massa et al., 2022). In order to characterize the stratigraphic setting of the shallow deposits (< 1500 m), in 2023 was acquired a 1.5 km long high-resolution reflection seismic profile at Vettabbia Park, through a linear array of 240, 4.5 Hz-geophones and a 6-tonvibratory seismic source (IVI-Minivib). The horizontal to vertical spectral ratio technique was applied to the ambient-noise and available earthquakes recordings to estimate the long-period ground motion amplification of the sediments. To determine the Rayleigh-wave dispersion curve, the passive array recordings were analysed by the frequency-wavenumber, the modified spatial autocorrelation and the extended spatial autocorrelation methods. In order to to obtain Vs profiles, joint inversions of Rayleigh-wave dispersion curve and H-over-V spectral ratio were analysed using "DINVER" and "JOINV6" codes. The latter has been constrained with the results from the 2023 high-resolution reflection seismic profile cited above. Both the Vs profiles were used to evaluate the seismic hazard through 1D equivalent-linear numerical models. Seismic inputs were selected according to the spectral form provided by the current Italian building-code NTC (2018) within the Milano metropolitan area. Normalized modulus reduction curve (G/G0-γ) and damping curve (D-γ) were estimated adopting the approach proposed by Darendeli (2001). Characteristics of amplification factors derived from geophysical surveys and numerical analyses were compared, pointing out their correlation with probabilistic seismic hazard of NTC (2018).

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ARISTOTLE-ENHSP project: a multi-hazard scientific expert advice service for the EC Emergency Response Coordination Centre

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Keywords: holistic early warning, 24/7 multi-hazard impact-oriented advice service at a global scale, Multi-national partnership.

The ARISTOTLE (All Risk Integrated System TOwards Transboundary hoListic Early warning) - ENHSP (European Natural Hazards Scientific Partnership) project delivers a flexible and scalable 24/7 multi-hazard impact-oriented advice service related to volcanoes, earthquakes, tsunami, severe weather, flooding and wildfires hazards at global level to the Emergency Response Coordination Centre (ERCC) of the European Civil Protection and Humanitarian Aid Operations Directorate (DG ECHO).

The service provided by ARISTOTLE operates in three modes; i) emergency (ERM), ii) routine monitoring (ROM) and iii) scientific expertise on-demand (SEOD) service. The ERM provides a comprehensive scientific assessment and advice to the ERCC within three hours from its activation. The ERM report can be full or lite depending on the specific nature of the hazard assessed; in both the cases, the weather conditions are always reported. The ROM is designed to provide three times per week a scientific assessment of the developing natural hazards at global level. Lastly, the SEOD service serves the ERCC to have direct scientist support in the case of major critical situations. This service is offered through various means and modalities both in presence at the ERCC headquarters and remotely.

ARISTOTLE includes 23 partners from 14 EU and non-EU Countries and from European international organizations operating in the Meteorological and Geophysical domains. Most of these partners have a format mandate to provide by law a surveillance service to the national Civil Protection Authority. To our best knowledge, ARISTOTLE is the first 24/7 virtual emergency room for multi-hazard assessment operating at global scale. ARISTOTLE remains a unique and world leading service and there is truly nothing internationally which even comes close to replicating a multi-national partnership which provides ‘actionable’ advice for operational purposes.

Preliminary geophysical characterization of the CSTH seismic station in the Campi Flegrei caldera (Southern Italy)

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Keywords: seismic site characterization, spectral analysis.

Local site conditions significantly influence the amplitude, duration, and frequency content of seismic recordings, making subsurface characterization a critical component of seismic hazard assessment. However, despite extensive research efforts, a universally accepted methodology for evaluating site effects is still lacking. Within this context, we present the preliminary steps in the site characterization of the broadband digital seismic station CSTH, operated by the Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano (INGV-OV), within the framework of the PON project *Geoscience Research Infrastructure of Italy* (GRINT). As part of the permanent seismic monitoring network in the Campi Flegrei caldera—among the most hazardous volcanic areas globally—this station plays a crucial role as a reference point for local seismic events.

To support its site characterization, a temporary 2D array of five short-period stations was deployed around CSTH, recording ambient noise and local seismicity over three days. Additionally, data from two nearby permanent broadband stations, CPIS and CSOB, were integrated to enhance spatial coverage and resolution. Spectral analyses, including Power Spectral Density (PSD) estimation, Horizontal-to-Vertical (H/V) spectral ratio analysis, and inter-station spectral ratios, were applied to assess frequency-dependent site responses and provide insights into local subsurface conditions.

Despite significant efforts to minimize anthropogenic noise—a persistent challenge in the densely urbanized Campi Flegrei area—data quality was affected by elevated noise levels, consistent with previous observations. The H/V spectral ratios obtained from both temporary and permanent stations were generally flat, lacking significant amplitude peaks. This suggests the absence of strong site amplification effects and supports the assumption of laterally homogeneous subsurface conditions across the study area. As a result, a one-dimensional (1D) S-wave velocity structure was considered a reasonable first-order approximation for the site. At the CSTH site, no fundamental resonance frequency was identified, and geological evidence excludes classification as a bedrock site. These results satisfy the first of the seven site characterization indicators, providing important constraints for subsequent steps.

These preliminary results demonstrate that, despite elevated environmental noise and geological complexity, robust information on local seismic response and subsurface structure can be obtained through careful analysis and integration of data from both temporary and permanent stations. A comprehensive multi-parameter site characterization, combining seismic and geophysical methods, is essential for constraining the shallow velocity model at CSTH and, more broadly, for improving the reliability of seismic monitoring and hazard assessment throughout the area.

Dimensional adaptation and monitoring of the weir on the Rio di Monte Porceddu in the Municipality of San Vito. Functional improvement, reduction of the risk of collapse (Provincia del Sud Sardegna)

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Keywords: risk management, natural hazard.

The Province of South Sardinia has been delegated by the Sardinia Region to carry out an urgent intervention to secure and functionally recover a dam in the riverbed, of the bridle type, designed to regulate the hydraulic flow of the "Rio Monte Porceddu", a watercourse tributary of the "Rio Corr'e Pruna". The main problem of the weir is linked to the risk of collapse of the structure due to the periodic erosion/accumulation phenomena to which it is subject. The large variations in hydraulic flow (torrent regime) have induced a strong regressive erosion of the downstream walls of the structure. Currently, there is a complete undermining of the foundation in correspondence with the central part of the work, originally sized in a non-optimal way, which has led to the excavation of the foot of the central part of the downstream wall. Following various surveys carried out on site, it was possible to observe how the variation of the flow and solid transport mechanisms, induced by the work have led to a decrease in the erosive phenomena of the natural riverbed, a decrease in solid transport due to a decrease in the natural slopes of the river. The project area is periodically subject to extreme rainfall events (Mediterranean cyclones), and currently it is necessary to implement the data regarding the flow and movement data of the accumulation areas, also for Civil Protection purposes. The restoration intervention is in the planning phase, multiple direct and indirect, geognostic and diagnostic investigations have been planned aimed at building the geological model of the terrain. To this end, particular attention must be given to the geomechanical characterization of the sediment and its "significant volume". The lithologies that characterize the intervention area concern both Paleozoic granitoid rocks and related acid and basic veins intruded into the batholiths involved, and the alteration materials organized in accumulation "glacis". The reconstruction of an accurate geological and geotechnical model of the terrain will lead to a better sizing of the new foundations and monitoring systems that will be installed, aimed at preventing the effects of flooding and flood events that affect the area. Monitoring stations for inclinometer and tiltmeter data of the artifact must be provided, in addition to the piezometric levels and volumetric variations of the flow rates, through laser and/or ultrasound devices, whose data can be processed in remote telemetric mode, the monitoring must therefore be shared and authorized by the authorities responsible for managing the hydraulic work, also identifying the body that will have to manage the transmitted data.

Indoor radon: from international regulations to Italian regional framework, with focus on potential exposure in Calabria (Southern Italy)

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Keywords: radon, PNAR 2023-2032, Calabria.

The regulation of exposure to ^{222}Radon (Rn), a radioactive gas recognised as a Group 1 carcinogen by the IARC, has become increasingly important throughout the world. However, the recommendations and standards for health protection are very different. The World Health Organisation (WHO) recommends a reference level of 100 Bq/m³ for indoor environments (Zeeb et al., 2009), emphasising the need to take corrective measures already at concentrations below the reference levels established in many national legislations. In the United States, the Environmental Protection Agency (EPA) has set an action level of 148 Bq/m³, whereas in Canada it is 200 Bq/m³. In Asian countries, attention to Rn risk has grown significantly in recent decades. In Japan, nationwide measurement campaigns led to the adoption of a guide value of 200 Bq/m³. In South Korea, the reference limit is 148 Bq/m³, and systematic measurement programmes in public and school buildings are performed. In China, the mapping of Rn concentration at urban and regional levels is supported by extensive experimental measurements. In Europe, the Directive 2013/59/EURATOM establishes an annual average concentration reference of air activity in workplaces of 300 Bq/m³.

In Italy, the European provisions were transposed by Legislative Decree n. 101/2020, and later supplemented by Legislative Decree n. 203/2022. The maximum reference levels, expressed as an annual average value of radon activity concentration in air, are i) 300 Bq/m³ for existing dwellings and workplaces, and ii) 200 Bq/m³ for dwellings built from 2025. The National Radon Action Plan 2023-2032 (PNAR), adopted by DPCM of 11 January 2024, establishes strategies for monitoring and reducing concentrations, with mitigation objectives in workplaces and homes. Among the actions envisaged, there is the identification of so-called “priority areas” - i.e. municipalities in which the percentage of buildings exceeding the reference level of 300 Bq/m³ is estimated to be greater than 15%, based on measured ground floor data. By the beginning of 2025, only 5 Regions had already identified priority areas, adopting quite different approaches from each other, ranging from log-normal distributions to geostatistical models and multivariate analyses, to lithological-based models.

Calabria is an area of particular interest, due to its geological complexity and peculiarities. In this regard, a study is currently underway to refine the map of areas expected to be at greatest exposure from indoor Rn, integrating the data collected by Lupiano et al. (2023). Initial results highlight the role of geological control factors (in addition to substrate and building characteristics) on the measured values. The study aims to methodologically support the identification of priority areas, providing a sound scientific basis for the implementation of effective mitigation strategies.

Lupiano V. et al. (2023) - Indoor Radon Measurements in Calabria (Southern Italy). J. Maps 19(1), 2132883, https://doi.og/10.1080/17445647.2022.2132883.

Zeeb H. et al. (2009) - WHO handbook on indoor radon - A public health perspective, 154767, https://www.who.int/publications/i/item/9789241547673.

Improving seismic risk assessment through 3D geological modeling: Insights from the Florence basin

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Keywords: 3D geological model, seismic risk assessment, Florence basin.

The effects of seismic events can be devastating, leading to loss of human life, damage to cultural heritage, and disruption of the social fabric. Assessing seismic risk and developing effective mitigation strategies remain critical challenges of this century.

Earthquakes are complex natural phenomena caused by the sudden release of energy, typically originating from a fault or fault system. Seismic ruptures occur at depth and generate waves that propagate through the Earth's crust and reach the surface.

The characteristics of seismic waves—and the resulting ground shaking at specific locations—depend on various geological factors, including fault architecture, rupture dynamics, and the physical properties of the rock volumes through which the waves travel.

Numerous studies have shown that local geological conditions significantly influence seismic wave amplification, resulting in site effects. These effects, observed in recent events such as the 2009 L'Aquila earthquake (Mw 6.3), are especially evident in sedimentary basins filled with alluvial material, where mechanical contrasts between bedrock and overlying sediments are present.

In this study, we integrated geological and geophysical datasets to construct a preliminary 3D geological model of the Florence Basin (Italy). Oriented NW–SE, the basin is bounded by the Apennine chain to the northeast and the Chianti hills to the southwest. Initial analyses reveal a complex substrate profile and intricate boundaries defining the sedimentary infill units.

Recent data—including a database of over 2,000 well logs, detailed gravimetric profiles, and a high-resolution DEM—have significantly improved our understanding of the basin. The non-uniform basement topography causes substantial variation in sediment thickness, reflecting alternating lithologies from different depositional environments. This lithological complexity influences the mechanical and physical behavior of geological units, with important implications for seismic wave amplification.

Amplification maps from recent microzonation studies reveal a marked spatial variation in seismic hazard. However, these 2D maps are insufficient for analyzing the full dynamic behavior of seismic waves in three dimensions.

Our study aims to develop tools and methodologies for 3D geological modeling based on the Florence Basin, a geologically complex case study. The approaches and results presented here are valuable for improving seismic risk assessments in similar settings. Enhancing local geological data supports more accurate 3D numerical simulations of ground motion, contributing to better mitigation strategies and more effective risk management.

Tight coupling of groundwater and sewer models for compound flood modelling in coastal urban areas

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Keywords: urban hydrology, groundwater, drainage networks.

Hydrological models often neglect the interplay of flooding mechanisms such as storm surge, rainfall, high tide, and groundwater emergence that may occur in coastal urban areas. Therefore, they could provide inadequate predictions. In this paper, we report on a study aimed at developing an algorithm to tightly couple groundwater and sewer models that could be applied to effectively evaluate grey and green infrastructure performance during compound flooding in coastal urban areas. The models developed in open-source programs such as MODFLOW and SWMM were coupled with a custom-built Python algorithm. The coupled models were calibrated and validated for a test site located in Long Island (NY, USA). Overall, tightly coupled MODFLOW and SWMM models can represent a substantial advancement in urban hydrological modelling, offering both immediate practical benefits for flood management and long-term strategic value for urban water infrastructure planning.

Decoding seismic site effects in coastal lowlands: a 3D stratigraphic perspective from the Pescara paleovalley

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Keywords: late Quaternary paleovalley, seismic site characterization, 3D modelling.

In highly urbanized coastal lowlands, seismic hazard assessments often rely on simplified engineering approaches, with limited consideration for detailed stratigraphic variability. In these settings, the thickness of Late Quaternary sediments exhibits marked lateral variability, frequently associated with buried paleovalley systems developed in response to glacio-eustatic sea-level fluctuations. These features generate complex subsurface architectures, where soft clay is encased within the stiff geological substrate. This study investigates the seismic response of a Late Quaternary paleovalley system beneath the city of Pescara (Central Italy). A comprehensive dataset, comprising 139 stratigraphic descriptions and two newly acquired reference cores, was integrated with a dense geophysical dataset including 134 microtremor measurements and five down-hole velocity profiles. Geostatistical interpolation of resonance frequencies revealed pronounced lateral variations, with low frequencies (~0.9 Hz) characterizing the paleovalley depocenter and higher frequencies (~4 Hz) delineating its margins. These variations, otherwise indistinguishable based on the surface geomorphology, significantly enhanced seismic hazard characterization and enabled a qualitative reconstruction of the buried valley system. The integration of stratigraphic and geophysical data allowed the development of a robust frequency-depth model and detailed 3D reconstruction of the paleovalley morphology. Analysis of down-hole shear wave velocity profiles identified five main seismic-stratigraphic facies, each distinguished by specific geophysical properties essential for accurate site response analysis. A simplified cross-section with five seismic layers was constructed and employed for ground motion analyses (GRA) through 2D finite-element modeling calibrated against measured geotechnical properties. The results reveal pronounced lateral variations in seismic response at resonance frequencies that align with microtremor observations, with amplification factors up to 4.6 at ~1 Hz in the depocenter and up to 2.5 at 4.5–5.5 Hz along the valley flanks, showing a strong control by the stratigraphic architecture. Furthermore, the construction of ten stratigraphic cross-sections enabled a high-resolution pseudo-3D reconstruction of the buried paleovalley geometry. This stratigraphic 3D modeling approach represents a crucial step toward comprehensive 3D ground motion analyses (GRA), providing a reliable basis for seismic hazard assessment in complex geological settings.

Geogenic radon risk in Italian show caves: a review

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Keywords: radon levels, health hazard, tourist caves.

The natural release of radon from rocks is one of the main environmental risk of ionizing radiation exposure affecting human health. This radioactive element derives from radium-226 decay into the crystalline matrix. Being a gas, radon diffuses into underground spaces, leading to dangerous concentration in poorly ventilated environments, such as caves. Radon level in karst systems is controlled by different factors, such as the underground geometry, the amplitude of the cave opening, the sediment filling composition, the external meteorology, etc., and it can vary spatially and temporally from a site to another. For this reason, it is very difficult to accurately predicting radon exposure in caves and its monitoring is important to perform radiation assessment of cave workers primarily to reduce the health risks.

Currently, more than 1,200 cavities worldwide are commercially exploited as touristic georesources (the so-called show caves) and in many countries they represent a very engaging and potentially competitive economic sector, favouring a rural development in remote area or extending the tourist period to the all seasons. In Italy, more than 60 natural caves are currently equipped for visits and show caves represent a valuable natural and cultural heritage, attracting hundreds of thousands of tourists every year.

In these peculiar underground work spaces, the radon concentration is regulated by the Italian Law 101/2020, which establishes a reference level of 300 Bq/m^3, expressed as the annual average value of radon activity concentration in the air. However, the geogenic nature of radon and the environmental conditions of caves, particularly the low ventilation and the variable microclimates, can lead to significant radon concentrations.

This review critically analyses and synthesizes the existing literature on radon concentration in Italian show caves with the aim to provide an up-to-date overview of the current knowledge on occupational health in tourist caves, to highlight the current problems in estimating the exact radiation dose for cave workers and to explore the future challenges for the implementation of the adopted regulatory frameworks of radiation protection with a specific protocol for cave environment mitigation.

How effective is seismic risk communication in Europe?

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Keywords: seismic risk, communication effectiveness, Europe.

Since the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015), the growing impacts of disasters have led to an increasing attention to the importance of communication in the different stages of the disaster life cycle: mitigation, preparedness, response, and recovery. In this study, we focus on seismic risk communication practices in Europe. Firstly, we statistically examine the growing trend of publications on the topic. Then, we delve into a specific topic: communication effectiveness. In particular, we explore methods and tools for the assessment of the effectiveness of different strategies. To do so, we build on a scoping review by Musacchio et al. (2023), which encompassed varying aspects of seismic risk communication in Europe, from 2000 to 2022. We have identified 48 out the 109 papers shortlisted by Musacchio et al. (2023) that delve into the topic of effectiveness. In addition to an analysis of the employed methodologies and tools, we examine the timing of the assessments and the impacts on recipients' knowledge and behaviors. We conclude by providing an overview of the main gaps, challenges and ways to evaluate risk communication practices.

Musacchio G. et al. (2023) - A scoping review of seismic risk communication in Europe. Front. Earth Sci., 11, 1155576, https://doi.org/10.3389/feart.2023.1155576.

UNISDR, United Nations International Strategy for Disaster Reduction (2015) - Sendai framework for disaster risk reduction 2015-2030, https://www.undrr.org/media/16176/download?startDownload=20240913.

Measurements of ^{222}Rn, ^{220}Rn, soil gas concentrations and groundwater compositions: case study of the Bojano Basin (Molise Region, Italy)

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Keywords: radon, aquifers, buried fault systems.

The Molise-Sannio region, located in the axial sector of the Southern Apennines (Italy), belongs to a fold-and-thrust belt shaped by Late Miocene to Early Pleistocene compressional tectonics, later overprinted by an extensional regime. This younger extensional phase, locally associated with strike-slip faulting in the northeastern sector, is responsible for the area's significant seismicity. Active faults in the region are capable of generating earthquakes with magnitudes exceeding 6.0. Within this framework, the MOSAICMO project (Molise SAnnio Integrated Crustal MOdel) was launched to develop a comprehensive, multiscale crustal model for the Molise-Sannio region by integrating seismological, geological, and geophysical datasets. A primary focus of the project is the Quaternary intramontane Bojano Basin. At present, the subsurface geometry and deeper structure of the Bojano Basin are poorly constrained, limiting the identification of master faults and the assessment of their seismogenic potential. Addressing this knowledge gap represents a key objective of the project, pursued through an integrated geological, geophysical, and geochemical approach. In this context, geochemical investigations involving soil gas and groundwater surveys were carried out to explore the fluid dynamics within the Bojano Basin. The strategy consisted of a series of profiles along the basin margins, designed to locate fault systems through direct and indirect methods. Soil gas concentrations of ^{222}Rn, ^{220}Rn, CO_2 CH_4, He, H_2 and light hydrocarbons were measured to characterize their spatial distribution, migration mechanisms, and to delineate high-permeability zones potentially associated with buried fault structures. Additionally, several major springs located at the basin margins were selected to identify potential patterns in deep fluid distribution. For each spring, physico-chemical parameters were measured, and water samples were collected for chemical and isotopic analysis. Soil gas surveys performed along multiple profiles revealed that the highest ^{222}Rn and ^{220}Rn values are consistently aligned with CO_2 anomalies, indicating prevailing advective gas migration, with CO_2 acting as a carrier for radon along preferential pathways. The results obtained from the gas-geochemical surveys correlate well with geophysical and geological data, offering new insights into subsurface fluid circulation during the interseismic period. The analysis of groundwater chemical composition further highlighted distinct flow systems within the Bojano plain, allowing the differentiation between deep circulation in carbonate aquifers and more superficial flow within Quaternary deposits. Overall, the soil gas technique proved particularly effective in a geologically complex environment characterized by alluvial plains, with ^{222}Rn measurements, often in combination with other gas analyses, demonstrating to be a cost-effective and rapid method for detecting buried fault systems.

Hazards are natural, disasters are not: are our risk mitigation efforts enough?

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Keywords: risk mitigation, natural and human-induced hazards, societies' resilience.

"Disasters are not natural" is a key message promoted by the United Nations office for Disaster Risk Reduction (UNDRR) under the 2015-2030 Sendai Framework (UNISDR, 2009). One of the major innovations introduced by this international treaty - building on the Hyogo Framework for Action (HFA 2005-2015) – is the shift in focus from "disaster management" to "disaster risk reduction". Yet, two decades after the first international steps to prioritize resilience, and with just five years remaining before the Sendai Framework's deadline, many targets are still far from being met (Zahid, 2024). The Framework's first priority, "understanding disaster risk", remains especially critical. Beyond assessing vulnerability and exposure, a deeper understanding of both natural and human-induced hazards is pivotal for effective risk mitigation and for building truly resilient communities. Our ability to anticipate the impacts of hazardous events depends first on the advancement of scientific knowledge, then on the capacity of academics to communicate that knowledge to policy makers, and finally on clear and timely communication with the public – on whom preventive and responsive measures ultimately rely. Investing in hazards knowledge is the foundational step toward predicting potential consequences in both space and time. Hazards also include latent conditions that may pose future threats, weather from natural sources (geological, hydrometeorological and biological) or human-induced processes (environmental degradation and technological hazards) (UNISDR, 2004). These latent conditions must be correctly understood, and addressed, to promote societies' resilience. These conditions must be thoroughly understood and addressed to strengthen societal resilience – a concept interpreted differently across research communities (Patel et al., 2017). While poor governance is often blamed when disasters strike, responsibility is usually shared among multiple actors, including academia, institutions and civil society. This paper presents selected Italian case studies of both geological and human-induced hazards (e.g., environmental degradation in industrial areas), illustrating how the integration of monitoring and environmental data can support stronger, more coordinated risk reduction strategies.

Patel S.S. et al. (2017) - What Do We Mean by 'Community Resilience'? A Systematic Literature Review of How It Is Defined in the Literature. PLoS Curr., 2017, 9, https://doi.org/10.1371/currents.dis.db775aff25efc5ac4f0660ad9c9f7db2.

UNISDR (2004) - https://www.unisdr.org/2006/highlights/2004/January2004-eng-P.htm.

UNISDR (2009) - http://www.unisdr.org/we/inform/terminology.

Zahid L. (2024) - Crisis Response: Sendai Framework's Hits and Misses. Int. J. Disaster Risk Sci., 16, 7-8, https://doi.org/10.1007/s13753-025-00616-7.

Coupling 3D geostatistics and 3D numerical models to characterize uneven land subsidence in Bologna, Italy

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Keywords: land subsidence, stochastically geostatistical modelling, numerical modelling.

Uneven displacements of the land surface, primarily driven by increased groundwater extraction, have emerged as a significant geohazard impacting numerous urban areas worldwide. This study introduces an integrated modelling framework combining 3D geostatistical, groundwater flow, and geomechanical models to investigate anthropogenic land displacements in regions characterized by heterogeneous lithological distributions. The city of Bologna, Italy, was selected as a representative case study due to the significant land subsidence experienced over the last decade and its complex architecture of alluvial fan deposits, making it an ideal location to evaluate the efficiency of this novel methodology. The study takes advantage of a huge dataset made available by the Environmental Protection Agency and the Geologic, Soil, and Seismic Survey of the Emilia-Romagna Region, including borehole lithological records, piezometric head distributions, groundwater pumping rates from the main four well fields used to supply potable water to the city inhabitants and from industrial wells, and precipitation recharge. The 3D geostatistical approach effectively reproduced the spatial distribution of lithofacies in the study area, where previous investigations highlighted the presence of the three distinct depositional domains with different stratigraphic architectures: the Reno River domain to the west with a gravel-dominated fill of a river valley, the domain of the Bologna urban area in the center, which represents a morphological and stratigraphic divide, topographically elevated with respect to the surrounding areas and characterized by fine-grained deposits, and the Savena River domain to the east with gravelly-sandy deposits. Significant differences in the facies correlation lengths have also accounted for to characterize the upper 100 - 150 m depth and the deeper portion of the aquifer system, with the former in the range of 100 to 500 m along the horizontal directions and the latter increased between 2000 to 5000 m. The 3D geostatistics model represents the foundation for accurately simulating groundwater head variations and consequent land subsidence and horizontal displacements over time and space. The outcomes of this research confirm the feasibility of the proposed modelling technique in complex geological environments and contribute toward establishing a systematic workflow that can be generalized for predicting and managing land subsidence risks in urban areas globally.

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In situ chemical imaging for the detection and quantification of asbestos fibres in synthetic materials (ACM) and natural rocks (NOA)

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Keywords: asbestos fibers, identification.

The commercial and regulatory term "asbestos" refers to a group of fibrous minerals, notably five amphiboles (crocidolite, amosite, anthophyllite, actinolite, and tremolite) and the fibrous polymorph of serpentine (chrysotile). Due to their unique physical, chemical, and mechanical properties, these minerals were extensively used in a variety of applications, including sound insulation and construction materials.

Although the use of asbestos fibres has been banned since '90s, the presence of asbestos-containing materials (ACMs) and naturally occurring asbestos (NOA) remains a significant concern for human health.

Accurate identification of asbestos fibres is essential for their safe removal and disposal. Over the past decades, various laboratory-based analytical techniques—such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX)—have been employed to characterize ACMs and NOA. However, these methods require sample collection, preparation, and laboratory analysis.

This study provides a comprehensive and accurate mineralogical multimethodological characterization of ACM and NOA samples, which could potentially be applied *in situ*. The results are validated through SEM-EDS mapping, confirming the reliability of the data and the potential for field-based asbestos detection (Marzini et al., 2025).

Marzini L. et al. (2025) - Identification, mapping, and quantification of asbestos minerals in ACM and NOA using NIR-SWIR hyperspectral scan imaging: Preliminary study. Spectrochim. Acta A: Molec. Biomolec. Spectr., 125893.

Integrating Bayesian updating and transition probability geostatistics for enhanced characterization of heterogeneous sediments

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Keywords: stochastic geological model, Bayesian updating, heterogeneous sediments.

The accuracy of hydrogeological simulations is significantly influenced by the geological heterogeneity of subsurface structures. The heterogeneity of sedimentary aquifers can be characterized by parameters related to the underlying sedimentary structure such as physical attributes of sediments (e.g., volume proportions and correlation lengths of facies types). Given the difficulty of obtaining lithologic data in the transverse direction, an assumption is often made that lithological characteristics are isotropic in the horizontal direction. This study integrates indicator kriging based on analytical solutions of transition probabilities with Bayesian-updated lengths of facies types to enhance the accuracy of geological structure simulations. Transition probability-based indicator kriging is employed to construct initial stochastic geological models. Bayesian update algorithm is subsequently applied to iteratively refine the lengths of facies types, which effectively incorporate observational information and reduce structural uncertainty. By directly using facies information in discrete boreholes, we first determined the volume proportions and the vertical mean correlation length of each facies. A series of facies sections along and perpendicular to the groundwater flow direction were used to determine the facies mean correlation length in the horizontal direction. Our results show that, by applying the Bayesian updating algorithm, the initially calculated lengths were further corrected, effectively avoiding biases due to incomplete exposure. The effectiveness of this method is validated in Cangzhou, Hebei Province, China. By integrating limited borehole data with facies sections, the consistency between simulated geological structures and observational data was significantly enhanced, and the associated uncertainties were effectively reduced.

Automated seismic detection of surficial mass movements for volcano monitoring: the Stromboli case study

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Keywords: tsunami hazard, seismic monitoring, volcano-landslide interactions.

Gravitational instabilities on active volcanic islands present a significant tsunami hazard, with waves capable of travelling vast distances and impacting far-off coastlines. However, monitoring gravitational mass movements in volcanic settings remains challenging due to limited data and the complex dynamics of volcano-landslide interactions. This hampers accurately identifying some landslide key source parameters. Stromboli, an active volcano in the Tyrrhenian Sea, frequently experiences various types of surficial mass movements (e.g. rockfalls, debris avalanches, and pyroclastic flows) along its Northwest flank, known as the Sciara del Fuoco. These events are closely monitored due to their tsunami-generating potential, as demonstrated during the 2002 eruption when two landslides produced ~2m high waves along the coast. Here we used seismic data from the Stromboli monitoring network to investigate patterns of landslide activity along the Sciara del Fuoco and their relationship with the persistent Strombolian activity. The primary objective is to develop near-real-time automatic algorithms aimed at retrieving some landslide key parameters, such as duration, run-out distances, path location, flow velocity, seismic energy and rate of occurrence. Monitoring these parameters provides valuable insights into ongoing volcanic processes and can help identify early warning signals for potential tsunami triggering. The study focused on the year 2020, a period marked by variable levels of volcanic activity. The automatic landslide detection algorithm developed in this study was tuned and validated using the landslide database maintained by the Osservatorio Vesuviano INGV, which is based on manual inspection of seismic records. A total of 457 landslide events—with an average duration of approximately 200 seconds—were automatically detected and analyzed during the study period. The daily landslide event rate ranged from 1 to 17 events per day. Notably, we found that the landslide rate increased prior to the brief eruptive phase of March–April 2020, a trend not captured by standard monitoring parameters such as volcanic tremor and seismic VLP event rate. By exploiting the decay of seismic amplitude, we were able to localize 41 landslide events. The preferred area for landslide occurrences was the northern summit sector of the Sciara del Fuoco, at an average elevation of 547 m a.s.l., typically characterized by average durations of 213 seconds and seismic energy releases ranging between 10^1-10^2 Joules. These landslides are typically triggered by pyroclastic fallout produced by Strombolian explosive activity. However, we also identified a number of higher-energy landslides (~103 Joules), originating from lower elevations and/or associated with pyroclastic flows triggered by more energetic explosions. These findings are vital for improving volcano monitoring at Stromboli volcano as the developed automatic algorithm can be incorporated into the real-time monitoring systems, improving early warnings of volcanic eruptions and tsunamis.

S31.

Landslide detection and forecasting: challenges and opportunities for Italian Geology

CONVENERS AND CHAIRPERSONS

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Automated detection and classification of active mass movements in SAR interferograms using a YOLO-based CNN

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Keywords: mass movements, InSAR, deep learning.

Slow mass movements are important players of landscape dynamics and pose significant threats to lives and infrastructures in mountain environments. They are characterized by different size and mechanisms depending on the materials involved, geological and geomorphological settings, and triggering factors. These processes exhibit different deformation patterns, with slow movements that endanger structures or evolve into fast movements and catastrophic collapse. To mitigate the related risks, slow mass movements must be promptly detected, classified and monitored over large areas.

During the last decades, optical remote sensing and spaceborne SAR interferometry proved powerful tools to complement the field geomorphological and engineering geological characterization of mass movements. However, limitations remain. Many mass movements are too fast for multitemporal InSAR and too slow for conventional optical or amplitude-based SAR analysis. Multitemporal InSAR products can fail detecting complex movements due to unwrapping errors, and a large part of the information recorded by InSAR phase is lost in processing. Modern SAR sensors allow obtaining high-quality interferograms, that offer a promising alternative for capturing slow mass movement signals. Nevertheless, noise, artifacts, and atmospheric disturbances make a reliable interpretation of deformation fringes challenging and time consuming.

To further exploit the information contained in wrapped DInSAR interferograms, in the MIRAGE project we developed a deep learning framework based on a YOLO convolutional neural network architecture, aimed at detecting and classifying different types of mass movement by analyzing deformation fringes. Inputs include the wrapped phase, a SAR signal reliability index incorporating geometric sensitivity and coherence, and a composite geomorphometric variable, that emulate the human expert interpretative process. For model training and validation, we developed an *ad hoc* geomorphologically constrained methodology to construct libraries of labeled InSAR phase signal, corresponding to the different types of mass movements recognized in two large (10^3 km^2) test areas in the italian Central Alps (Lombardia) and Apennines (Emilia-Romagna), representative of contrasting para-periglacial and fluvial-dominated geomorphic environments. Preliminary results show a good capability to detect and classify the different types of mass movement processes. This demonstrates the strong potential of our model to use readily available InSAR products to streamline the rapid generation and updating of active mass movement inventories, supporting local monitoring strategies, civil protection actions and data integration into landslide modelling.

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Integrating multi-platform InSAR data and multi-temporal inventories for enhanced dynamic landslide hazard assessment in Belluno province (Veneto region, NE, Italy)

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Keywords: landslide, InSAR, forecasting.

Landslides are a major geological hazard, particularly in alpine environments where slope deformations pose significant risks to infrastructure, ecosystems, and communities. The Belluno Province, located in the Veneto region (NE Italy), features complex topography and diverse geological formations, making it highly susceptible to landslide activity. To enhance risk assessment and mitigation strategies, the integration of multi-sensor data with dynamic hazard mapping is essential to improve accuracy and effectively monitor landslide activity. This study integrates Interferometric Synthetic Aperture Radar (InSAR) derived by the processing of COSMO-Sky-Med and Sentinel-1 SAR images and multi-temporal landslide inventories to develop a dynamic landslide hazard assessment framework. By leveraging multi-sensor datasets and spatial analyses, this research provides a comprehensive evaluation of landslide susceptibility and activity over time. Landslide inventories were derived from orthophotos obtained via WMS and WMTS from the Italian national portal, covering the period from 1989 to 2021. The study focuses on the Cordevole and Alpago region of the Belluno Province, situated in the northeastern Italian Alps. These areas were affected by two extreme meteorological events with return periods exceeding 100 years: the VAIA windstorm (October 27–30, 2018), which caused widespread deforestation and landscape destabilization, and a subsequent event from December 4–6, 2020, which further intensified slope instabilities. By incorporating multi-sensor observations and a dynamic mapping approach, this study provides critical insights into the temporal evolution of landslide-prone areas. Moreover, the methodological framework enhances the broader understanding of landslide dynamics in alpine environments, providing an adaptable approach for hazard assessment in similarly vulnerable regions.

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Geodetic-topographic and multi-technical monitoring (UAV/RTK) of the landslide that affected the urban area of Motta Sant'Anastasia (CT), Sicily

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Keywords: geodetic-topographical monitoring.

Defining the kinematics and the dynamics of active geological processes is a useful practice to study these types of phenomena; this kind of knowledge is achievable by monitoring the studied processes using geodetic and topographic technique. Monitoring must be calibrated by the analysis of spatial-temporal factors that define the rate of the deformation, such as preliminary stratigraphic and structural geological surveys, followed by geomorphological, hydrological, and geotechnical studies. In this work, the research team of the Geodynamic & Geomatic laboratory (University of Catania), in collaboration with the municipality of Motta Sant'Anastasia, exploits the use of a GNSS monitoring network to define the kinematic of a landslide affecting the north-eastern edge of the Motta S. Anastasia village (Catania). The landslide body develops to the east direction and is made up by chaotic clays and sands, (Servizio Geologico d'Italia, 2010). The landslide encloses part of the urban area and its crown is delimited by fractures that crop out on walls, asphalt and buildings. The geological setting is characterized, in descending stratigraphic order, by superficial alluvial deposits transitioning into gravelly sands, sands, sandy clays, and grey-blue Plio-Pleistocene clays interbedded with sandy lenses of probable volcanic origin. This layer represents preferential pathways for water infiltration and has been identified as the landslide slip surface. Since January 1984, stabilization works have been implemented, including the construction of a retaining wall and concrete sub-drainage wells. On May 2023, we installed three permanent stations (one external, one internal, and one near the landslide crown), and eleven benchmarks along the retaining wall. In June 2024, the monitoring system was integrated with photogrammetric surveys by UAV on the eastern sector of retaining wall, using a Phantom 4 PRO V.2.0. Ground Control Points (GCPs), placed on wells constructed in the 1980s, were georeferenced using RTK GNSS system. The images were processed by Agisoft Metashape in order to generate point clouds for each survey. In order to assess potential subsidence of the wells, distributed along the landslide, the point clouds were compared using CloudCompare software (Cloud-to-Cloud tool, Z component). Moreover, the results of the GNSS monitoring show no significant displacements at points located outside the landslide, while the permanent station and the points inside the landslide recorded eastward movements of up to 12.7 mm/month. Preliminary UAV and RTK surveys suggest a vertical subsidence of the wells ranging from 0 to 7 mm/month and a horizontal displacement rates between 1 and 13 mm/month respectively, confirming the ongoing activity of the landslide.

Servizio Geologico d'Italia (2010) - Carta Geologica d'Italia alla scala 1:50.0000, F. 633 Paternò. ISPRA, Roma.

Geomorphological-structural analysis of the landslide slope on the left hydrographic side of the Cercevesa stream, in Paularo (UD)

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Keywords: landslide, 3D models, structural analysis.

Friuli Venezia Giulia region (NE Italy) shows a high vulnerability to hydrogeological instability, due to the combination of a predisposing stratigraphic and tecnonic setting, High-relief morphology, and a climatic regime characterized by intense precipitation. These factors contribute to the frequent triggering of landslide phenomena. Within this framework, the present work focuses on the geomorphological and structural analysis of a major gravitational landslide located on the left bank of the Cercevesa stream, in the municipality of Paularo (UD), within the mountainous territory of the Carnic Alps. The study area is characterized by high tectonic complexity, resulting from the superposition of two distinct orogenic events: the Hercynian and the Alpine. The landslide, active since the early 1990s, has shown progressive acceleration over time, with significant implications for geomorphological hazard and hydrogeological risk.

The objective of this research was to develop a comprehensive and multidisciplinary understanding of the landslide through the integration of traditional methods and innovative technologies. Bibliographic and field data were combined with advanced remote sensing and 3D modeling techniques, including LiDAR derived DTM (Digital Terrain Models), 3D models produced by means of aerial photogrammetry using the Structure from Motion-Multi View Stereo (SfM-MVS) method, radar interferometry (DInSAR).

This work, let us constraint for the first time, this landslide as a predominantly roto-translational one, with localized rockfall events near the crown trench. The affected area covers approximately 12.5 hectares, with an estimated volume of 6.5 million cubic meters. Temporal analysis revealed significant morphological changes, also correlated with seasonal rainfall patterns. Geometric analysis of the spatial variations within the landslide body, conducted using cloud-based algorithms over an eleven-year time span, showed a maximum displacement of 13 meters, corresponding to an average velocity of 9.8 centimeters per month.

Structural analysis, based on the extraction of best-fit planes and subsequent calculation of fold axes, identified a single deformational phase attributable to the Hercynian orogeny.

The results of this work not only fill a significant knowledge gap in a geologically critical area but also provide practical tools for future slope stability assessments, land-use planning, and the design of risk mitigation strategies.

Inferring rainfall thresholds for shallow landslide occurrence by means of data-driven approach and multitemporal landslide data

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Keywords: landslide hazard, rainfall threshold, multitemporal landslide inventory.

Landslide hazard maps allow identifying areas prone to slope failure by providing landslide probability over a given return period. Hazard maps incorporate the temporal dynamics of triggering events, such as intense rainfall (Corominas et al., 2014). Methods for landslide hazard estimation mainly depend on data availability. Physically-based approaches assess hazard by evaluating slope stability using sets of geotechnical/hydrological parameters (e.g., critical rainfall thresholds; Weidner et al., 2018). Hence, they are less suited for regional analyses, where data-driven machine learning methods are preferred. The latter methods rely on "historical" data linking rainfall to landslides via empirical thresholds (e.g., intensity-duration curves; Segoni et al., 2018). They can incorporate rainfall variability or be applied with incomplete datasets, but the uncertainty about the landslide triggering date hinders their implementation. For the CARG sheet F. 249 "Massa Carrara" (ca. 600 km2), we developed a multitemporal inventory of shallow landslides (1954–2021) based on the classification and interpretation of a multitemporal set of aerial images with 2-10 years temporal resolution. While the landslide triggering dates are typically unknown, we can define their temporal occurrence window (TOW) as the time interval between the oldest image in which the landslide is mapped and the most recent antecedent image. To estimate and map the rainfall thresholds for shallow landslide occurrence (RT), we consider daily rainfall, as this parameter is available at the rain gauge stations for the time interval of the inventory. Moreover, we assume that, during the TOW, the daily rainfall event(s) that occurred were intense enough to exceed RT. Then, we perform the following steps to map RT and its return period: (a) generating a stack of daily rainfall maps (1954–2021) with Universal Kriging method, using elevation as a secondary variable (Hiemstra et al., 2009) to process data from 122 rain gauge stations; (b) extracting daily rainfall time series for landslide locations and selecting the most intense daily events (> 99.5th p.) recorded before and during the TOW; (c) partitioning the study area into sets of unique condition units (UCUs) and grouping landslides by UCU; (d) for the landslides of each UCU, extracting RT, i.e. the daily rainfall maximizing the accuracy of a confusion matrix based on the distribution of intense daily rainfalls occurred before/during the TOW; (e) for UCUs without landslides, the maximum recorded rainfall is assumed to represent the lower limit of RT; (f) evaluating the RT return period based on the statistical analysis of the yearly maxima of daily rainfall. We apply the above steps for different sets of UCUs to obtain pixel-by-pixel distribution/statistics of RT. Despite uncertainties and the need for further refinements, results suggest that the method provides promising insights for shallow landslide hazard mapping at regional scale.

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Does inventory matter? A comparative landslide susceptibility assessment using a new multitemporal shallow landslide inventory and IFFI in the Alpi Apuane (Italy)

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Keywords: data-drive susceptibility modelling, IFFI, landslide inventory.

Shallow landslide inventories are fundamental inputs for susceptibility modelling, yet their construction methods, resolution, and objectives can affect modelling results. In this study, we assess the sensitivity of landslide susceptibility models to inventory characteristics by comparing two inventories for the Alpi Apuane region (Northern Tuscany, Italy): the official Italian national inventory (IFFI) and a new, high-resolution, multitemporal shallow landslide inventory (DBSL) developed for this research.

The DBSL was obtained by integrating semi-automatic classification and visual interpretation of a multitemporal set of orthophotos acquired during ten epochs from 1954 to 2021. The inventory includes ~1,000 shallow landslides, a subset underwent field validation and analysis to collect type of movement and materials. The analysis of spatial and temporal distribution highlighted relationships with intense rainfall events, morphometric conditions, lithology and engineering geological settings. On the other hand, IFFI is a national-scale inventory compiled from different heterogeneous sources and criteria, with limited landslide temporal information and, at least in the study area, underrepresentation of shallow landslides.

Both inventories were used to develop susceptibility models through data-driven methods: logistic regression and random forest. Predisposing factors included morphometric variables, lithology, land use and a newly developed near-surface engineering geological classification of bedrock units. This latter layer obtained by integrating fieldwork observations and laboratory tests proved to be effective in highlighting intra-formational engineering geological variations relevant to slope stability. Preliminary results indicate that susceptibility maps derived from DBSL and IFFI significantly differ in spatial patterns, predicted probabilities, and accuracy metrics. DBSL - based models outperform IFFI - based ones in both resolution and prediction performance, especially in areas affected by recent rainfall-triggered landslides. Moreover, IFFI - based model appears to miss key morpho-lithological controls that are captured by using the DBSL.

This study is part of a broader hazard mapping project (CARG project, "Landslide hazard map", F. 249 "Massa-Carrara"), where the availability of IFFI prompted a critical evaluation of its suitability and performance for susceptibility modelling. While IFFI remains a valuable reference, the DBSL is proposed as a complementary inventory, better suited for high-resolution susceptibility shallow landslide modelling, as well as hazard analyses.

Our findings highlight that the inventory choice influences modelling performance and the outcomes of the hazard – vulnerability – risk analysis chain. Hence, although high-quality, validated inventories such as the DBSL require considerable resources, they are crucial for robust hazard and risk assessments.

Approaches to landslide susceptibility mapping in Italy based on deep feed-forward neural networks

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Keywords: landslide, deep learning, susceptibility mapping.

Landslide susceptibility mapping is a strategic topic in Italy, given the diffuse presence of landslides, which expose a huge number of urbanised areas and infrastructures to geo-hazard. For this reason, it is of foremost importance to have knowledge of these phenomena in terms of their location and the influence of local conditioning factors on their activity. The large availability of geodatabases for the whole Italian territory fosters the use of approaches able to process massive quantities of data, i.e. big data, and extract new information by learning from them. Among such approaches, deep feed-forward neural networks (DFFNN) (Hakim et al., 2022) are particularly promising, since their complex and multi-layered architectures are particularly suited for processing large, unstructured databases, such as those available for landslides. One of the main issues is the choice of a proper dataset of conditioning factors to be used as inputs. From a computational efficiency point of view, the numerosity, in terms of variables, should be optimised in order to avoid the involvement of variables which poorly affect landslide susceptibility. Scientific literature proposes a number of possible variables (Ghorbanzadeh et al., 2022; Azarafza et al., 2021), however, the proper choice is related to local features, such as geomorphological and geological characteristics of the investigated area, besides the prevailing typology of landslide. A further point is the mapping strategy: DFFNNs allow for detailed mapping (Ngo et al., 2021), like pixel-based approaches, where the analysed area is discretised on the basis of a grid and every element of the grid is mapped. This is a very detailed mapping, which literally allows for drawing the areas susceptible to landslide phenomena, however, this approach can be computationally hard, thus limiting the extension of the investigated areas and the dimension of the grid elements. An alternative is the identification of landslide susceptible areas as a single point. This can significantly reduce the amount of processed data, but this poses the problem of associating spatially distributed variables with a single point. Here, some examples are provided, comparing the aforementioned different approaches and analysing the influence of different conditioning factors on mapping landslide susceptibility. Landslides used for training DFFNNs are extracted from the Italian Landslide Inventory Map (IFFI), in order to compare different approaches starting from the same database. Variables used as conditioning factors are extracted from processing Digital Elevation Models (DEMs), maps of use of soil, lithological maps and land cover maps. These are all datasets easily available for the entire Italian territory. The outcome of this analysis shows the pros and cons of the proposed approaches, looking at the practical uses of these applications for geohazard management and mitigation.

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Integrating InSAR displacement time series and geospatial data for large-scale classification of active ground deformation areas in Italy

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Keywords: landslide, active ground deformation areas, artificial intelligence.

Ground deformation, resulting from both natural processes such as landslides and deep-seated gravitational slope deformations (DSGSDs), and human activities like mining and subsidence, poses significant threats to infrastructure and human safety. Accurate classification of these deformations is crucial for national land use planning. Most existing classification studies focus either on analysing temporal deformation trends from time series data or on classifying manually selected features using machine learning, with limited efforts to combine both sources of information. Our research aims to bridge this gap by exploring a multimodal learning framework that fuses temporal and spatial features for the classification of ground deformation processes.

To address this challenge, we constructed a comprehensive dataset of Active Deformation Areas (ADAs), defined with the ADA finder tool (Navarro et al., 2020). For each ADA, we extracted both ascending and descending InSAR displacement time series from the European Ground Motion Service (EGMS) and corresponding Sentinel-2 imagery, DEM, slope, aspect. We developed a dual-branch deep learning model, where one branch is designed to extract features from the time series and the other from the spatial image data. These features are then fused using a Long Short-Term Memory (LSTM) module for final classification. To better understand the internal decision-making logic of the model, we further applied explainable AI (XAI) techniques to identify the most influential time steps and spatial patterns contributing to each predicted class.

Results, using cross-validation, show that the model achieves an overall accuracy of over 90%. This demonstrates its effectiveness and robustness in handling diverse deformation types. We subsequently deployed the validated model and classify all ADAs generated for the entire Italy. XAI analysis confirms that the model leverages meaningful physical patterns from both temporal and spatial inputs, thus enhancing its scientific interpretability and potential for operational use.

This study provides a novel and scalable framework for ground deformation classification by leveraging the strengths of both temporal and spatial data. The classification achieved can lead to better-targeted risk mitigation strategies, and improved ground motion forecasting and early warning systems.

Navarro J.A. et al. (2020) - ADAtools: Automatic Detection and Classification of Active Deformation Areas from PSI Displacement Maps. ISPRS Int. J. Geo-Inform., 9(10), 584, https://doi.org/10.3390/ijgi9100584.

Integrating XAI and GNSS to determine rainfall triggers for large-scale landslide events

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Keywords: landslides, GNSS and rainfall monitoring, landslide early warning system.

Landslides are a widespread problem in Italy, but landslides early warning systems (LEWS) can reduce and mitigate this danger through non-structural actions. Research on LEWS has advanced significantly in the past decade due to better monitoring and data analysis, though identifying landslide triggering factors remains challenging since they change over time and space. Nevertheless, a full understanding of these factors is relevant for the assessment of natural hazards. The combination of recent low-cost GNSS instruments and other available monitoring systems of precipitation can enhance a LEWS. A continuous early warning system applied to a large landslide as a tool for analyzing the role of rainfall as a driver for the landslide has been applied to a complex landslide in the Carnic Alps in North-East Italy. The Cazzaso deep-seated landslide monitoring system, deployed since 2016 by the CRS (OGS) in agreement with the regional Civil Protection, continuously records displacement measures from 12 GPS + 2 GNSS stations, thus providing optimal temporal coverage of the data. Displacement time series from the geodetic stations and precipitation data from 2 pluviometers have been analysed and compared. By applying a velocity threshold to the geodetic data, it was possible to create an inventory of landslide reactivation events, a novel aspect that provides valuable insights for conducting important analyses and enhancing or updating a LEWS. The Cazzaso landslide shows to be primarily triggered by rainfall, leading researchers to initially apply empirical rainfall thresholds (Intensity-Duration, or I-D thresholds) to define warning levels for an early warning system. However, the validation of these thresholds showed poor performance, likely due to the complexity and depth of the landslide, which cannot be fully captured by simple statistical methods. Therefore, a more advanced approach using a Random Forest (RF) model combined with Explainable AI (XAI) techniques has been adopted. In particular, Out-Of-Bag Error (OOBE) has been used to assess the importance of different variables, and Partial Dependence Plots (PDPs) have been employed to visualize their influence. The machine learning analysis identified 8-day cumulative rainfall as the most effective predictor of landslide reactivation, enabling the definition of reliable thresholds to support the GNSS-based warning system. This approach not only improves operational early warning but can also be adapted to evaluate the impact of short- and long-term rainfall in varying geological and climatic conditions. Although the system is site-specific, its structure outlines a useful guidance for similar cases and may even be applicable in broader contexts.

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Playing with risk: Safe Haven – Landslides as a serious game for interdisciplinary geo-risk communication and community resilience

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Keywords: risk communication, preparedness, serious games.

In the face of growing climate-related risks and geo-hazards, innovative and accessible communication strategies are essential to overcome linguistic, cultural, and emotional barriers. Safe Haven - Landslides, a tabletop serious game developed within the Horizon Europe "The HuT" project, offers an engaging tool that integrates science, play, and narrative to communicate the complexity of landslide risk.

Designed for high school students, educators, and local stakeholders, the game transforms abstract risk dynamics into tangible experiences, fostering collective dialogue and critical thinking around disaster preparedness and mitigation. Through a cooperative card-based system, players manage a fictional region threatened by landslides, exploring the interplay of environmental, social, and infrastructural factors. The game setting invites discussion not only of technical strategies but also of values, priorities, and emotional responses in the face of natural disasters.

In this sense, Safe Haven supports a form of learning that bridges disciplines and encourages empathy — essential for building resilient communities. A structured evaluation framework, based on pre- and post-game questionnaires, has been employed to assess changes in knowledge, perception, and engagement.

Preliminary results indicate a measurable improvement in understanding landslide risks and proactive management strategies. Moreover, the format is being adapted to other hazards such as floods and heatwaves, further broadening its communicative scope.

By blending scientific content with play and storytelling,Safe Haven - Landslides, exemplifies how serious games can serve as transdisciplinary tools for geo-risk education and cultural resilience. The project aligns with the vision of using creative approaches to promote sustainable land management and meaningful dialogue between communities, scientists, and decision-makers.

Improving regional-scale prediction of rainfall-induced landslides by coupling satellite-based products and machine learning

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Keywords: early warning, shallow landslides, machine learning.

In Italy, landslide alerts are issued for territorial units named alert zones (AZ), covering a few thousand km^2. Usually, regional-scale landslide early warning systems (LEWSs) rely on rainfall thresholds, which require a few parameters and provide clear results in short computational times. However, a model at AZ scale may miss some local features relevant for landslide initiation. This could hamper an effective warning by producing incorrect predictions. On the other hand, machine learning (ML) techniques offer the advantage of incorporating multiple geoenvironmental factors and have been widely applied to generate landslide susceptibility maps. However, these methods are constrained to spatial predictions, limiting their applicability to LEWSs.

This work aims at improving the operational regional-scale prediction of rainfall-induced landslides by means of a multi-scale approach, taking advantage of both satellite-based rainfall products and ML tools.

A dynamic ML methodology using the Random Forest (RF) algorithm (Nocentini et al., 2024) is defined in order to generate daily landslide hazard maps, including temporal and spatial probability of landslide occurrence. The proposed approach involves using a temporally-explicit landslide inventory and identifying non-landslide events over time and space. This allows the integration of dynamic rainfall data (both daily and antecedent rainfall) with traditional static geoenvironmental factors (like lithology and geomorphologic attributes).

Landslide information comes from the ITALICA landslide catalogue (Peruccacci et al., 2023), which provides high temporal accuracy (the time or at least the day of occurrence is known) and accurate localization. Hourly rainfall estimates are retrieved from GPM IMERG LatePrecipitation V6 at 0.1° resolution (55 grid cells). The use of slope units instead of pixels enhances the representation of geomorphological processes. The model was trained and tested in the Ligu-C Alert Zone (Liguria region, northern Italy), an area with complex geology and high mean annual rainfall (> 3000 mm). Subsequently, the generated predictor model was applied successfully simulating a peculiar intense rainfall event, demonstrating its high reliability in distinguishing stable from unstable conditions.

Results confirm the potential of dynamic RF models to overcome the limitations of static ML approaches, providing useful outputs for operational LEWSs. An extension of this methodology to other Italian study areas with different geoclimatic contexts and its validation against independent datasets are foreseen.

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Machine learning algorithms for landslide susceptibility mapping applied on Portofino promontory (Italy)

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Keywords: landslide susceptibility map, machine learning algorithms, imbalanced landslide datasets.

Rainfall-triggered landslide susceptibility maps (LSM) identify landslide-prone areas, providing valuable support to decision-makers in defining risk reduction strategies. They provide relevant data for spatial planning, preventing urban development in high-risk areas, and enhancing early warning systems. The present research is part of the RAISE project, funded by the Ministry of University and Research (MUR) under the National Recovery and Resilience Plan (PNRR). The main objective is to identify the most reliable machine learning approach to build LSM in the Liguria Region (Italy). In particular, the present research aims at comparing LSMs elaborated using different machine learning algorithms, applied to the Portofino Promontory (Liguria – Italy), where widespread shallow landslides are triggered due to the occurrence of intense and short-duration rainfall events. In the investigated area, the susceptibility map elaborated by Roccati et al. (2021) employing the semi-quantitative analytical hierarchy process (AHP) method is assumed as the benchmark. The proposed methodology considers the same natural and anthropogenic conditioning factors and the same 110-year inventory of rainfall-triggered landslides, including 102 landslide events, of the mentioned work. As the number of landslide samples is lower than samples with no landslides, adversely affecting the performance of machine learning algorithms, different techniques of data balancing have been applied to the original dataset. The balanced dataset was then used to train and test Random Forest, Light Gradient Boosting and Easy Ensemble Classifier state-of-the-art classification algorithms. Several metrics, such as recall, accuracy, F1 score, are used to compare the performance of the algorithms. The calibrated algorithms have been applied to the investigated area, providing for each pixel a probability of landslide occurrence, then categorized into 5 susceptibility classes (very low, low, medium, high, very high). One limitation of the use of machine learning algorithms for decision-support tools lies in their interpretability. Feature importance analysis was performed to quantify the relevance of each conditioning factor, contributing to enhancing machine learning model's interpretability. Also, SHAP (SHapley Additive exPlanations) was applied to further investigate the role of each variable in the model predictions. The obtained LSMs were then compared to the LSM elaborated by Roccati et al. (2021), as well as to the river Basin Management Plan in use (Autorità di bacino distrettuale dell'Appennino settentrionale, 2025), through performance of the Cohen's Kappa coefficient. Further applications to different sites affected by rainfall-triggered landslides need to be carried on to define the reliability of the models for landslide susceptibility map at the regional scale.

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Landslides and extreme rainfall in the Northern Apennine (Italy): two case studies

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Keywords: extreme rainfall, landslides.

Extreme weather events are becoming more frequent and severe, as evidenced by the Mediterranean region's experience with the new phenomena of Medicanes. The rise of average temperature and wide temperature gradients, extensive air instability, and maximised potential moisture transport into the region are some of the preconditions that have led to such extremes. These events have had extremely detrimental consequences on the ground, resulting in geo-hydrological dangers that were frequently unforeseen. Assessing the impact of climate change on landslides makes it necessary to build and update landslide datasets in a timely manner allowing the comparison with previously-event mapped landslides. The research wants to explore the consequences of extreme weather conditions of distinct meteorological origins that had a significant impact on the slope stability of two regions in the northern Apennine Mountain chain (Italy) in 2022 and 2023. A strong self-regenerating storm system struck the Marche region in 2022, bringing heavy precipitation with notable peaks exceeding 400 mm. In 2023, the Emilia-Romagna region saw two consecutive episodes in less than 20 days, with some locations receiving more than annual total amount of 450 mm of precipitation. An Atlantic-based occluded weather front that was fed by a Mediterranean storm was responsible for the last two events. Certain climatic factors—most notably, protracted prior drought periods—were shown to be contributing to the land disturbance in both situations. The well-known landslides propensity of these places makes it possible to have a good knowledge of the landslides in the area as evidenced by the availability of a large database. This made it possible to compare ordinary landslides and those triggered by extreme events. Based on post-event inventories, only a minor percentage of the landslides triggered by the extreme events derived from the reactivation of the previously mapped ones and further, they did not consistently exhibit the same kinematics. This suggests a lack of continuity in the landslide dynamics or real reactivation. This resulted in a number of typological and spatial evaluations of newly occurring events in comparison to those that had already been mapped. These were then correlated with other features of the region, including lithology, slope orientation, and connectivity, which were evaluated alongside the distribution of precipitation. We were able to observe the many controls they had in producing various kinds of occurrences thanks to these connection analyses. In order to fully understand the slope evolution under unusual and extreme rainfall and, ultimately, evaluate the dependability of current mapping for such conditions. Although landslides constitute a major threat to people worldwide, resulting in fatalities, significant damage, and significant financial losses, it is crucial that current maps be updated and serve as the foundation for new research.

Hydrogeological investigations in slow-moving landslides: two case studies in the Susa Valley (NW Italy)

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Keywords: displacement rates, groundwater level, statistical analyses.

Mountainous regions are particularly prone to ground instabilities due to their geomorphological features and the impacts of climate-related events (Narcisi et al., 2024). Slow-moving landslides, such as complex-type or Deep Seated Gravitational Slope Deformation (DSGSD), which involve large slope volumes, can undergo significant acceleration in response to seasonal rainfall and snowmelt. Displacement rates are closely linked to changes in groundwater level, which represents a key mechanism driving slope movements. Consequently, quantifying the influence of precipitation on recharge processes and, in turn, on displacement trends is essential for understanding slope dynamics.

The Susa Valley, located in the NW of the Piedmont Region (Italy), is a clear example in this context. This study investigates the relationship between groundwater fluctuations and displacements trend at two landslide sites (Champlas du Col and Thures), which are affected by huge deformations that have repeatedly damaged buildings and infrastructure. Leveraging suitable monitoring data, provided by ARPA Piemonte, the proposed methodology integrates statistical tools to analyse the behaviour of the time series and offers a promising approach for forecasting landslide deformations (Liu et al., 2025). The presence of monitored water springs provides valuable insights into aquifer dynamics and their data were compared with displacements from automatic inclinometer probes for both sites. Using this approach, displacements trends could be inferred directly from variation in groundwater levels, presenting a preliminary, cost-effective alternative to more expensive and invasive deep movement monitoring systems.

The results highlight the role of spring water levels as a powerful tool for the detection of deep landslide movements, especially when the spring and inclinometers are located close to one another and are influenced by the same landslide dynamics. For instance, in the Thures landslide, spring water level trends reliably predict acceleration phases. Conversely, in the Champlas du Col landslide, the discrepancy between spring and displacement trends suggests the presence of a sub-landslide within the main body. Given the complexity of this phenomenon, a numerical model was developed to simulate the hydromechanical response of the Champlas du Col slope under different scenarios, including snowmelt, intense rainfall and cumulative long-term precipitation (Cappa et al., 2014). A series of numerical simulation was performed using a simplified model of the landslide body to evaluate transient pore pressure variations and the saturation process resulting from a gradual rise in the groundwater table combined with infiltration (Yang et al., 2017). The effects on slope stability were then assessed by comparing safety factors before and after triggering events.

This approach provides a realistic representation of the mechanisms involved and enhances understanding of the deformation rates over time, allowing for the identification of threshold values resulting from the combined effect of snowmelt and precipitation.

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Deep learning-based landslide displacement forecasting: a comparative study across diverse geographical and triggering scenarios

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Keywords: landslide, Conv-LSTM.

Landslides are one of the most destructive natural disasters in the world, causing significant economic loss and fatalities. To reduce these consequences, developing precise early warning systems (EWS) for landslide movement is crucial. The application of machine learning (ML) and deep learning (DL) algorithms have recently achieved notable success in landslide prediction, especially with time-series datasets. Nowadays, research focuses only on particular types or region of landslide, making it difficult to apply these findings elsewhere. This research aims to fill this gap by testing the performance of seven advanced DL algorithms, including Multi-Layer Perceptron (MLP), Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), 1D Convolutional Neural Network (1D CNN), 2xLSTM, Bidirectional LSTM (Bi-LSTM), and Conv-LSTM Hybrid, on four contrasting landslide scenarios. The case studies differ geographically, geologically, and in their triggering mechanisms such as rainfall and reservoir-induced water level changes. The study is conducted using topographic and remote sensing data like GNSS and InSAR to construct the forecasting models. The Conv-LSTM model demonstrated superior performance in highly seasonal landslides, while MLP, LSTM, and GRU models resulted in most consistent and accurate results across non-seasonal and less periodic landslide settings. The study highlights that 1D CNN and Bi-LSTM models are less effective in predicting landslide displacement, primarily due to their inability to capture the complex temporal dependencies inherent to landslide dynamics. One key finding of the study is the importance of selecting a DL model based on the landslide's seasonal characteristics and the nature of the displacement triggers. While the Conv-LSTM model is particularly suited for landslides with pronounced periodicity, the MLP, LSTM, and GRU models perform more robustly in varying conditions, including slow-moving and rainfall-induced displacements. The study emphasizes the need for a tailored model selection strategy when deploying DL-based landslide EWS. The findings suggest that a combination of models, particularly leveraging Conv-LSTM for seasonal cases, can improve the accuracy and reliability of landslide predictions.

Monitoring ground movements using EGMS data: development of an integrated methodological approach for the analysis of potential and critical issues to support land management

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Keywords: European Ground Motion Service, deformation, monitoring.

Monitoring and analysis of ground motions are essential for hazard mapping and assessment, geo-risk management and land planning. Among the available resources, the European Ground Motion Service (EGMS), developed under the Copernicus programme, provide systematic and high-precision coverage of European ground deformations at local and regional scales through satellite radar interferometry (InSAR) techniques. However, to ensure a correct and effective use of these data, it is necessary to define adequate operational procedures and shared interpretation criteria.

This study focuses on the development of a methodological approach and the interpretation of EGMS data with the available geological, geomorphological and territorial information from Regional Geoportals for hazard zoning. It is therefore proposed to explore in a systematic and analytical way the potential and critical issues related to the use of EGMS data for land use planning and prevention of geological risks.

The adopted approach comprises several methodological phases, starting with the pre-treatment selection of the data, keeping Ascending and Descending orbits separate to ensure a more accurate characterization of ground deformations, to move then to the application of quality criteria to the interferometric data, and then to the classification of PS, based on the significance of the deformation rates. The deformation rates have been analyzed with respect to reference thresholds, allowing a distinction between negligible and significant movements. Through a process of data selection and cross-referencing, known unstable areas are mapped and analyzed, and new unstable areas are identified.

The results of this work allow to identify possible technical and operational solutions useful to support a more aware use of EGMS data in the context of land management and risk mitigation.

Unravelling the complexity of interplaying mass movements in periglacial environments using radar, optical and thermal remote sensing: the case of Val Cedec (Central Alps)

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Keywords: periglacial mass movements, multi-sensor remote sensing, Central Alps.

Steep rock slopes in alpine periglacial environments are shaped by complex interactions between weathering, debris production and different types of mass movement processes, all with potential hazard implications. Climate-driven permafrost degradation can initiate slow mass movements, destabilise rock glaciers, and predispose slopes to catastrophic failures. To investigate these dynamics, we selected a permafrost-affected rock slope in Val Cedec (Central Alps, Italy) as a natural laboratory, consisting of a 750-meter-high glacial valley flank carved in phyllitic mica-schists with elevations up to 3000 m.a.s.l.

First, we delimited the main geomorphological domains through fieldwork observations and exploration of aerial images and DEM-derived products. To characterise ground displacement patterns, we used satellite-based DInSAR techniques from C-band Sentinel-1 images collected between 2017 and 2024. These datasets were processed using dual-pass DInSAR, stacking and multi-temporal techniques, aimed at distinguishing the kinematics and displacement rates in each geomorphological domain. We also applied optical offset tracking techniques with Sentinel-2 images to estimate faster movements, which are typically hindered in DInSAR analysis. In addition, we explored the relationship between permafrost occurrence and slope dynamics using thermographic techniques, using imagery from both the Landsat-8 satellite and a high-resolution infrared camera during field surveys conducted in July 2021 and August 2024.

Our results revealed a complex interplay among shallow periglacial mass movements and slow deep-seated slope deformation, including sectors with distinct kinematic behaviours. In the middle slope sector, two rock glaciers are present, one showing evidence of destabilisation. Further downslope, two large solifluction lobes complexes redistribute debris fed by fractured permafrost-affected rock masses. By exploring wrapped interferograms with different temporal baselines (6 and 12 days, 1 and 3 months, 1 year), we detected a high temporal variability of both displacements and coherence among different geomorphological domains. These observations clearly outline the limitations of multi-temporal DInSAR in the analysis of complex and heterogeneous mass movements. Thus, we estimated displacement by counting wrapped interferometric fringes to obtain approximate time series of displacements over different domains, while we estimated the faster movements (> 0.5 m yr^{-1}) through spaceborne offset tracking. Displacement rates and trends show relationships with the likelihood of permafrost occurrence and temperature variations during snow-free seasons, suggesting that permafrost degradation and seasonal changes in the active layer play a role in the present-day evolution of slope stability conditions.

Satellite-based monitoring and landslide analysis following extreme rainfall event: the case of Modigliana (FC)

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Keywords: landslide monitoring, inSAR, artificial intelligence.

In May 2023, Emilia-Romagna and Tuscany were hit by two exceptional rainfall events, characterized by intense and prolonged rain that caused widespread flooding and triggered about 80.000 landslides (Berti et al., 2024).

The Department of Geosciences at the University of Padua conducted a detailed analysis of the landslides that occurred in the Forlì-Cesena province, particularly in the Modigliana area, where the landslides caused damage to infrastructures and disrupted the operation of an important gas pipeline.

The study involved the processing and interpretation of both optical and radar satellite data with focus on InSAR data from the SAOCOM satellite constellation. The analysis enabled the assessment of landslide activity and deformation trends of slopes. The resulting data was then compared to time series data from the ALOS-2 satellite. Progressive ground movements were identified, some of which occurred before the event, and were attributable to a gradual weakening of the mechanical resistance of the flysch formations in the area.

In addition to the radar data, landslide mapping was carried out using high-resolution optical imagery, applying a hybrid approach that combines artificial intelligence techniques with traditional methods. The results highlighted a widespread occurrence of shallow sliding landslides. This integration of datasets allowed for cross-validation and evaluated the potential of InSAR data in monitoring long-term slope instabilities that could trigger or reactivate landslides during extreme weather events.

Furthermore, the use of U-Net convolutional neural networks applied to PlanetScope imagery enabled the production of rapid and accurate maps of the affected areas, later validated through field surveys and comparison with the detailed manual mapping conducted by the Emilia-Romagna Region.

The study can be subdivided in two phases: the first consists of a detailed analysis that was conducted on the Via Lago landslide, which interrupted the gas pipeline. It reveals a progressive instability of the uphill slope, with increasing deformation rates before the May 2023 landslide event, indicating a gradual failure evolution or tensile fracturing processes.

In the second phase, two other landslides located in the study area are going to be analysed. InSAR data collected after the event of 2023 will be processed and correlated with ground-based monitoring data. This will allow for a comparison with potential external drivers helping to improve risk prevention and management strategies.

Berti et al. (2024) - RER2023: the landslide inventory dataset of the May 2023 Emilia-Romagna meteorological event. Earth Syst. Sci. Data, 17(3), 1055-74, https://doi.org/10.5194/essd-17-1055-2025.

Synergistic use of InSAR and high-resolution optical data for ground deformation assessment in the NW Himalaya

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Keywords: InSAR, land subsidence, landslides.

The Himalayan Region is prone to surface deformation phenomena, including land deformation, earthquakes, landslides, and extreme climatic events. The Doda region in Jammu and Kashmir has recently faced increasing risks of land subsidence and landslides due to its complex terrain, uncontrolled development, and severe climatic conditions. This study introduces a comprehensive method for detecting and monitoring ground instability through a combination of Synthetic Aperture Radar (SAR) and optical remote sensing data.

We incorporated optical data from PlanetScope imagery by applying time-series deformation analysis using Sentinel-1 SAR imagery based SBAS-InSAR processing. This merger enabled precise mapping of active deformation zones, particularly near Thathri and Assar, connecting ground movement to surface conditions and human-driven factors. The findings reveal significant subsidence hotspots and areas vulnerable to landslides, providing crucial information for reducing disaster risks. This study illustrates the benefits of using multi-sensor data for effective geohazard monitoring in the Himalayan regions, facilitating informed planning for resilient infrastructure in the Chenab Valley.

Real-time monitoring of rapid slope hazards through radar doppler in Italy

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Keywords: Ground-Based Doppler Radar (GBDR), slope hazard, monitoring.

Ground-Based Doppler Radar (GBDR) is an innovative technology that addresses hazards in steep mountainous terrains. Rockfalls, rockslides, ice and snow avalanches pose significant risks to human lives, infrastructures and ecosystems. These phenomena, classified as 'very rapid' and 'extremely rapid', sometimes exhibit minimal deformation before failure, making early detection challenging (Hungr et al., 2014).

GBDR offers a promising solution for real-time, long-range, and wide-area monitoring of rapid slope hazards. This technology enables timely alerts once the phenomenon has been triggered, allowing an instantaneous response to mitigate risks in vulnerable areas. Additionally, GDBR data allows for reconstructing runout trajectories, which is crucial for calibrating mitigation measures and prioritizing structural interventions to protect the elements at risk (Viviani et al., 2020).

In Italy and around the world, GBDR has been successfully deployed at a limited number of sites, addressing various types of gravitational deformation, from rockslides (e.g., Ruinon landslide) to ice-rock avalanches (e.g., Marmolada glacier). In particular, to monitor the active translational rock-debris slide of the Ruinon landslide, a GBDR connected to a traffic light system has been deployed. The rapid debris movement revealed individual boulders that reached 10m in diameter and posed a serious rockfall hazard to the downslope road. Continuous monitoring through the GBDR and road closure in response to movements mitigated the risk (Carlà et al., 2024). Another example of an operational use of GBDR is the ice-rock avalanche that affected the upper portion of Marmolada glacier in July 2022, resulting in eleven fatalities and seven injuries. A GBDR was installed to continuously monitor the source area of the avalanche and alert the personnel assigned to rescue operations in the event of any new movement.

Recently, a GBDR has been installed to monitor a sub-vertical granitic slope, 500 meters high, above the Gallivaggio sanctuary (Central Italian Alps), specifically to detect rockfalls ranging in size from thousands of cubic meters to approximately one cubic meter. Since 2016, a Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) has continuously monitored the highly active slope, which in 2018 experienced a major rockfall. This event involved the detachment of a block of approximately 5000 m^3 from the upper part of the slope, causing significant damage to the sanctuary and road (Carlà et al., 2019). To our knowledge,this is the first instance of GBRD being deployed to monitor such a steep, acute-angled slope alongside an existing monitoring system.

This work presents preliminary results of these monitoring activities, highlighting the potential of GBDR technology to enhance slope monitoring and risk mitigation strategies in mountainous regions.

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Carlà T. et al. (2024) - Real-time detection and management of rockfall hazards by ground-based Doppler radar. Landslides, 21(1), 155-163, https://doi.org/10.1007/s10346-023-02144-1.

Hungr O. et al. (2014) - The Varnes classification of landslide types, an update. Landslides, 11(2), 167-194, https://doi.org/10.1007/s10346-013-0436-y

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Combination of *in situ* and remote data detection method for earthquake-induced landslides

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Keywords: earthquake-induced landslides.

The management of hazards and risks associated with environmental effects induced by earthquakes, such as landslides, requires a thorough study of historical data. This helps in understanding the geographical distribution of these effects based on earthquake parameters (Guidoboni et al., 2019; Zei et al., 2024) and in defining empirical relationships that are useful for assessing risk and damage.

Historically, direct field observations have been employed to identify earthquake-induced effects. However, these observations do not always provide a complete picture of the issue, particularly in extensive epicentral areas during emergencies.

In contrast, new technologies, such as satellite imagery analysis, are valuable for rapid responses and assessing the impact of earthquake-induced effects. Nonetheless, due to their inherent limitations—such as resolution and availability— these technologies can only be regarded as a partially exhaustive tool for a complete impact assessment.

Therefore, in this study, we propose a method that integrates both direct and indirect observations to comprehensively map the effects of earthquake-induced landslides in the epicentral area. This approach facilitates a rapid response during emergency phases and creates a data set representative of the event, which is beneficial for refining empirical relationships related to earthquake-induced landslides.

We have applied this method in a test site from Italy, specifically the Montecilfone area (CB) affected by an earthquake on August 16, 2018, which had a magnitude of 5.1. We identified earthquake-induced landslides based on the delineation of the epicentral impacted area, applying the empirical relationships developed by Cinosi et al. (2023). Next, we selected satellite images acquired before and after the seismic event. These images were then processed using a method called Normalized Differences Index (NDI), which automated the identification of ground variations attributable to landslides (Valkaniotis et al., 2024). Indirect observations and automatic effect mapping obtained from remote data were subsequently combined and calibrated with direct observations from field surveys.

This procedure is essential, as preliminary detection of objects from remote sensing data requires verification of data reliability. As a result, a semi-automatic mapping was conducted, verifying: a) the traceability of elements identified by the normalized difference index to seismic-induced landslides, and b) the correspondence between detected effects and those identified remotely. This method, which combines data from various sources, generates a dataset that supports a comprehensive assessment of earthquake-induced landslides in the epicentral area. The application of the proposed method to other areas will allow for the improvement of empirical relationships. This analysis represents an effective tool for detecting landslides triggered both by earthquakes and extreme precipitation events.

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S32.

Sustainable utilization of water resources under the effects of climate changes and hydrogeochemical risks: multi -proxy approches from monitoring to the modelling and management

CONVENERS AND CHAIRPERSONS

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Soil, water, sun: exploring ungrafted indigenous Italian *Vitis vinifera* L. varieties as a resilient resource against the effects of global climate change

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Keywords: climate change, ungrafted grapevines.

Climate change effects on grapevine and its products, such as intensified aridity, increased soil salinity, heat stress, and more frequent extreme weather events, are well-documented at regional, national and international levels (Gambetta et al., 2020). Ungrafted grapevine varieties (*Vitis vinifera L.*), representing unique genetic resources capable of thriving in challenging soil conditions, offer an opportunity to assess their potential as valuable assets for enhancing resilience against climate change, particularly in marginal viticultural zones. "Soil, water, sun: Exploring Ungrafted indigenous Italian *Vitis vinifera L.* varieties as a resilient resource against the effects of global climate change (EU-Vitis)" is a collaborative research project started in February 2025 and developed jointly by scientists of the University of Ferrara and the University of Calabria, with the scientific support of the Council for Agricultural Research and Economics, Research Centre for Viticulture and Enology (CREA-VE), also actively involving local viticulturists. The main aim of the EU-Vitis project is to establish a robust scientific foundation for understanding the connections between pedoclimatic characteristics, the physiological performance of these ungrafted vines, and the compositional characteristics of their grapes. The current distribution of these self-rooted ecotypes is limited to a few regions in Italy, where they have been historically protected from the grapevine phylloxera. EU-Vitis strategically focuses on geographically diverse experimental sites: the sandy coastal areas of Emilia-Romagna and the hilly terrains of the Calabria region. The variety in genetic resources, geomorphological features, soil types, and the presence or absence of grafting at these selected locations provides ample experimental material for conducting comparative field analyses. As a preliminary step, the site investigation was started and is ongoing to collect historical and field data of selected vineyards. The final objectives are (i) to increase the knowledge of self-rooted vines and their environment; (ii) to collect detailed datasets concerning soil characteristics, vine physiological behaviour and grape quality parameters, as well as information on wines; (iii) to identify significant relationships among the monitored parameters; (iv) to increase awareness of the value of self-rooted vines in stakeholders, also by proposing geomarkers of product authenticity.

EU-Vitis will construct rich datasets concerning self-rooted vines and their territory, identifying robust indexes linking soil-plant-grape-wine to promote knowledge-based approaches for more resilient viticulture in a changing environment.

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Water quality and pollution risk assessment of groundwater and surface water of the Oreto basin area (Sicily, Italy)

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Keywords: hydrogeochemisty, water-rock interation, qanat.

The Oreto River fed mainly by runoff from the southwestern flank of the Palermo mountains, extends for ~20 km within a watershed of ~130 km². The Palermo Plain consists of a Pleistocene calcarenitic-sandy aquifer with variable permeability. The river is characterized by strong seasonal variability: in winter, water abundance re-establishes water and ecological continuity along its course, while in summer, low flow and hydrodynamic stasis promote temperature rise and decomposition, leading to reducing conditions and dissolved oxygen depletion. These conditions have been established in the terminal stretch of the Oreto as far back as past centuries and worsened recently due to urban and industrial pollution. Decreased flow in summer increases solutes up to nearly toxic levels, impairing the life of animal and plant species. However, due to the high self-purification power of the river, related to the permeability of the substrate, and the action of the flora, concentrations do not reach toxic levels, maintaining a tolerable ecological balance despite anthropogenic pressures.

The objective of this study is to assess the accessibility and quality of the waters through hydrogeochemical and microbiological investigations. Many sampling campaigns have been made on both surface and groundwater, during dry and rainy periods, to measure the main physicochemical parameters (EC, T, DO, Eh, and pH) and to analyze: major dissolved constituents (Na, K, Ca, Mg, S, Cl, F, N, Alk); trace elements (Li, Be, B, Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Rb, Sr, Mo, Ag, Cd, Sn, Sb, Te, Cs, Ba, Tl, Pb, Bi, U); chemical oxygen demand (COD); Escherichia coli. Sampling sites include the main springs, wastewaters (untreated or partially treated), various sites along the river channel, including the mouth, the wells, and some qanats which are ancient underground channels built by the Arabs for irrigation purposes.

The waters have a bicarbonate-alkaline-earth composition, resulting from water-rock interaction processes, and reflect the dominance of limestones in the area. The effects of anthropogenic pressure on the river become more evident in urban areas, where untreated effluents significantly impact water quality: negative Eh, decreased DO, increased EC, and elevated COD and N species. Many trace elements (Cu, Pb, Ni, Cr, Fe, Al, Sb, and Sn) also increase from the sources to the estuary, pointing to an anthropogenic origin. A clear indication of anthropic impact, primarily from domestic wastewaters, is provided by the high levels of Escherichia coli found in many of the sampled sites, often exceeding the legal limit. Despite growing public attention on this important river, which represents a vital ecological corridor within the city, numerous issues, related to widespread domestic and agricultural pollution, remain. This study aims to provide a large unpublished dataset for future actions to reduce the anthropogenic impact on this crucial regional water resource.

Integrated analysis of deep aquifers in Western Sicily using well data and 3D hydrogeological modelling

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Keywords: deep aquifers, groundwater exploration, water supply.

Sicily lies in the central Mediterranean and is known as a region vulnerable to drought, with conditions expected to worsen under climate change. Also considering that Sicily's economy relies heavily on agriculture, which accounts for approximately 70% of the region's water use, make a priority a more effective water management and the exploration of new and unconventional groundwater sources.

This study focus on the Western Sicily, spanning both onshore and offshore between Sciacca, Palermo, and Trapani. Geologically, this area belongs to the Apennine-Tyrrhenian system, specifically to the Apennine-Maghreb orogenic belt and the Pelagian-Sicilian Thrust Belt.

Multiple data sources were integrated, including cartographic material, bibliographic studies, and publicly available deep wells and seismic data from the VIDEPI project, a database that includes information on exploration and production hydrocarbon wells drilled in Italy between 1957 and 2015, offering valuable stratigraphic, lithological, geophysical, and fluid content data.

Our work followed three main phases: a screening phase involving literature review, data gathering, and log digitization and cartographic data management using QGIS; a focus phase centered on the analysis of well data, including formation top reconstruction and deep fluid test interpretation (DST and Production Test); and a modeling phase dedicated to the creation of 3D hydrogeological models focused on some specific area of interest.

Outputs include pressure, salinity, and piezometric maps that help in defining fluid distributions and in identifying areas with potential fresh to brackish water deep reserves. The project led to the identification of several geological situations with deep freshwater/low-salinity aquifers, which were then investigated using a 3D modelling approach. The resulting 3D reconstruction offers insights into the spatial configuration and connectivity of deep aquifers, with the final aim to contribute to regional strategies definition for a sustainable water resource utilization. While further validation is needed, the findings offer a foundation for future applied research and groundwater management initiatives.

Water isotopic composition of Hellenic karst spring waters

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Keywords: karst springs, isotope, hydrogeochemistry.

The isotopic composition of atmospheric precipitation, expressed as δ^2H and $\delta^{18}O$, is a useful tool for climatological and hydrogeological research. Isotope hydrology provides insights into the local hydrological cycle, the spatial and temporal variability of atmospheric composition, the relationship between atmospheric composition and local environments, as well as processes on a regional scale.

In this study, we present the results on the isotopic composition of water from the main carbonate aquifer in Greece. From 2018 to 2022, 202 water samples were collected from across the entire Hellenic territory, mostly from springs with flow rates exceeding 50 L s^{-1}. These water samples were analyzed for their isotopic composition at the INGV-PA laboratories.

The values of $\delta^{18}O$ ranged from -10.6 to 1.6 ‰, whilst the δ^2H results varied between -72.3 and -2 ‰. Samples that may have been significantly affected by evaporation, were excluded from the calculation of the meteoric water line. Moreover, some springs are situated in coastal areas, and their chemical composition (Li Vigni et al., 2023) evidenced the presence of marine water contamination. In these cases, the isotopic composition of the carbonate springs was recalculated by accounting for the percentage of seawater, derived from chloride concentrations. Finally, we computed a local meteoric water line, as follows:

$$\delta^2H = 8*\delta^{18}O + 16.5$$

The results are closely comparable with the Greek meteoric water lines obtained by previous studies and represented by the following equations:

$$\delta^2H = 8*\delta^{18}O + 15$$
$$\delta^2H = 8*\delta18O + 19.5$$

as calculated by Argiriou & Lykoutis (2005) and Dotsika et al. (2010) respectively.

The isotopic data from the karst spring waters has also been used to estimate a vertical isotopic gradient. The estimated gradient is of 0.32‰ $\delta^{18}O$ each 100 meters, which is higher than the vertical gradient of 0.21‰/100 meters calculated previously (Dotsika et al., 2010). This study focuses exclusively on big karstic springs, which are hosted by aquifers comprising thick carbonate formations affected by karst circulation. This process leads to significant vertical water movement, facilitating the discharge of isotopically lighter rainwater at lower elevations (Minissale & Vaselli, 2011).

Lastly, the deuterium excess was evaluated, showing a range from 7.4 to 22.6 ‰. Crete Island exhibited higher values compared to continental Greece. This suggests a different source of the rainwater due to the position of the island in the middle of the eastern Mediterranean sea.

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Identifying unconventional fresh-to-brackish groundwater reserves by using a multi-proxy dataset: insights from the North Adriatic Sea (Italy)

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Keywords: unconventional groundwater reserves, hydrostratigraphy, Quaternary.

Fresh-to-brackish groundwater preserved in continental shelves may represent an unconventional yet strategic source of water to help mitigate future water crisis (Bakken et al., 2012), not only as potable water but also as cost-effective raw water for desalinization (Jones et al., 2019). This is especially true in many coastal areas worldwide, where freshwater reserves are generally overexploited and increasingly threatened by seawater intrusion. Furthermore, the offshore extent of coastal aquifers could be taken into account for the water storage planning in the near feature. In this framework, the reinterpretation of pre-existing stratigraphic, hydrogeological, geophysical and chemical data from public databases, and the coastal-to-shelf correlation of twenty-six well logs, led to the identification of fresh-to-brackish groundwater reserves within a multi-layered aquifers' system extending up to 60 km offshore the Italian coast. A first volume assessment revealed that ca. 26.7 km^3 of fresh water and ca. 33.4 km^3 of brackish water are stored within the North Adriatic (NA) shelf deposits. Freshwater is contained between 0-300 m depth, in Middle to Upper Pleistocene fluvio-deltaic sands characterized by high resistivity (> 15 ohm*m) and representing the seaward extension of the coastal aquifers. Resistivities gradually decrease with depth and toward distal sectors, to values typical of sediment including brackish water (15-5 ohm*m), saline water (5-2 ohm*m), and seawater (< 2 ohm*m), thus suggesting water mixing possibly due to aquitard/aquiclude heterogeneity. This multi-proxy investigation reveals that the formation and the current configuration of Early-to-Middle Pleistocene offshore aquifers in the North Adriatic resulted from the combination of tectonic activity and eustatic sea-level oscillations. These two driving factors acted concurrently until the last major Apennines uplift event, dated to about 450 ka BP (Regione Emilia-Romagna & ENI-AGIP, 1998). On the other hand, in the contest of tectonic quiescence, over the last 450 ka, Milankovitch-driven (100 ka) sea-level variations have played a dominant role in groundwater emplacement. Our findings may provide new insights for the exploration of unconventional sources of water, and new perspectives for planning its strategic storage and sustainable exploitation.

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Multiscale hierarchic 3D modelling of karst aquifers: from representation of large-scale hydrostratigraphic units to groundwater circulation patterns

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Keywords: Campo dei Fiori, geomodels, stratigraphy.

Karst aquifers in mountain areas are important groundwater resources whose management requires reliable hydrogeological models. This study aims to develop the 3D hydrostratigraphic conceptual model of a karst aquifer group, combining geological mapping with a multi-scale and hierarchic approach for 3D modelling. We focus on the karst aquifer systems of the Campo dei Fiori massif (CdF; Lombardy, Italy). The target hydrostratigraphic architecture encompasses Triassic carbonate platforms and the configuration resulting after Jurassic rifting of the western Lombardy Basin (Monte Nudo Basin and Arbostora Swell) and subsequent alpine polyphasic thrusting and folding.

The 3D geological model is constrained to geological maps and cross-sections and was computed based on the potential field interpolation method of 3DGeoModeller®. The geologic entities were ordered into a hierarchic pile, permitting to codify the lithological variability and the chronology of the geo-history. The relationships set between folds, faults and lithosomes drove the modelled cross-cut relationships coherently with the geological evolution. Within the main CdF aquifer group, the lower aquifer systems, with dominant karst dispersive circulation mode, are hosted by Triassic platform dolostones lapping onto the Palaeozoic basement aquitard, (fissured, massive intrusive rocks of the Arbostora swell). The upper aquifer systems are characterized by karst drainage circulation through large, pervasive and connected cave systems, located within the Jurassic and lower Cretaceous basinal limestones. The interference of alpine thrust-folding stages with the basin-and-swell configuration inherited from the Jurassic rifting set the hydrostructural features of the CdF Massif. The Arbostora/CdF anticline, the inverted Marzio fault and the associated conjugate sets of normal and reverse faults, deploy the subsurface watersheds and interconnections among the spring clusters.

The 3D model permits to draw the separators between the aquifer systems and to hypothesize the location and shape of the subsurface watersheds. The relationship with the deployment of springs, helps to identify the recharge areas and the eventual interconnections between the different spring clusters, by comparison with the monitoring data collected at selected springs (hydrographs, hydro-chemical and hydro-physical parameters).

The 3D hydrostratigraphic model shows how the stratigraphic and structural evolution set i) the hierarchy of karst aquifer systems and separators, ii) the subsurface catchments nested within them and the permanent or transient nature of their boundaries dependant on recharge dynamics changes. The model is predisposed for hydrogeological modelling, since it allows to inspect the location of springs in relation to subsurface separators and watersheds. Due to its hierarchic and multiscale nature, the proposed approach can be applied to study areas of different extent and degree of geological complexity.

Assessment of a coastal fresh groundwater extending deep and offshore southern Sicily (Italy), *via* petrophysical and 3D hydrogeological modelling: the case of the Ragusa aquifer

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Keywords: petrophysics, offshore freshened groundwater, coastal aquifers.

Sicily is among the region most vulnerable to drought, with conditions expected to worsen under climate change, underscoring the urgent need for sustainable water management and the exploration of unconventional water resources. Mediterranean region has faced increasingly frequent and severe droughts, with Sicily particularly exposed due to its geographical location and climatic conditions. Searching for sustainable sources of water becomes a critical priority to ensure the resilience of local communities, agriculture, and ecosystems. This study investigates the Ragusa Oligo-Miocene Formation, a karstified and fractured carbonate aquifer with medium to high porosity, which outcrops across the Hyblean Plateau in southern Sicily and was originally deposited in a ramp environment. The primary objective is to assess the deeper and offshore extension of this carbonate aquifer along the southeastern coast, where it is sealed beneath more recent deposits: along the coastal area and offshore, Plio-Quaternary sediments overlay the carbonate deposits of the Ragusa Formation, confining the aquifer and preserving its water resources. Mapping the extension of the Ragusa aquifer beneath these younger deposits is essential to evaluate the potential of fresh groundwater resources at greater depths and offshore. Data from 90 deep oil and gas wells, both onshore and offshore, were analyzed to reconstruct the Ragusa subsurface geometry. The availability of the dataset, originally acquired for hydrocarbon exploration, offers a unique opportunity to reinterpret the subsurface geology from a hydrogeological perspective. Well logs, core descriptions, and stratigraphic records provide detailed information on lithology, porosity distribution, and structural features. Geophysical logs were examined using petrophysical methods and quantitative log inversion to assess the presence of fresh groundwater. In particular, geophysical logs were analyzed through petrophysical classification of lithologies and the development of quantitative inversion models to estimate key parameters such as porosity, water conductivity, and fluid salinity. The log's inversion was carried out using techniques that integrate Spontaneous Potential / Gamma Ray, Resistivity, and Sonic logs responses to derive continuous profiles of rock properties in the geological formation under analysis. At the same time, hydrogeological data from shallower onshore water wells were integrated to refine the regional aquifer system. The study results indicate clear evidence of fresh/freshened groundwater within the Ragusa aquifer, extending deeper than previously known onshore and continuing offshore up to 10 km from the coastline. A first conservative volumetric calculation estimates about 3 Km^3 of fresh groundwater preserved offshore of the study area, at depths between 500 and 1200 m below sea level. This discovery has significant implications for developing an unconventional potable water source, offering a potential solution to Sicily's long-term water scarcity challenges.

Distribution of Potentially Toxic Elements (PTEs) in two mine-impacted watersheds and implications for toxic elements discharge in the Mediterranean Sea in changing hydro-climatic conditions

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Keywords: contaminant hydrology, antimony province, stream sediment.

The spatial and temporal variability of ore-related PTEs contents were assessed in stream sediments across the Tafone and Chiarone creek catchments (Central Italy), which drain part of the dismissed Southern Tuscany Sb ore Province and discharge their solid load into the Mediterranean Sea. Samples were collected in 2024 along the Tafone and Chiarone main courses and tributaries for the determination of Sb, As, Hg, and Tl concentrations and results were compared to data collected in 1985 and 1997 after mine decommissioning. In 2024, apart from Tl, the PTEs showed mean concentrations that exceed the Italian safety limits for public green soils (Legislative Decree, 152/2006), with maximum values of 344.4, 163.2, 16.6, and 3.3 mg/kg for Sb, As, Hg, and Tl, respectively. Antimony exceeded the safety limits for soils (10 mg/kg) throughout the two catchments, particularly downstream of the main mine sites (i.e., Tafone, Montauto, and M. Capita). Arsenic and Hg showed the highest concentrations in the upstream section of the Tafone watershed, where the most important dismissed mines lie. Conversely, the Chiarone basin showed weaker pollution for the latter two elements. Thallium frequently exceeded the safety limit of 1 mg/kg (up to 3.3 mg/kg) along the tributaries that drain the area comprised between the M. Capita and Macchia Buia mines. The Tafone Creek showed a weak downstream attenuation of Sb, As, and Hg pollution, with concentrations up to 44.4, 30.4, and 3.7 mg/kg, respectively, close to the outflow into the Mediterranean Sea. The comparison of 2024 results with 1985 and 1997 data shows that a decrease of contamination is occurring over time preferentially in the upstream section of the Tafone and Chiarone watersheds, but not in their downstream parts. Therefore, these creeks show a low resilience to PTEs pollution, and they represent a persistent source of toxic elements for the Mediterranean Sea. The discharge of the polluted mass load from the watersheds to the sea could be enhanced by the changing hydrometeorological patterns: most of the yearly precipitation is progressively occurring in short time spans but with high intensity. Consequently, the increasing occurrence of flashfloods will enhance the delivery of the toxic elements from the two basins to the Mediterranean Sea.

The Farfa river and spring in Sabina (province of Rieti): an example of overlooked hydrogeology and history

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Keywords: Farfa river, geochemistry, groundwater-surface water interaction.

The Farfa river is a tributary of the Tiber river on the left bank, upstream Rome in Central Italy. It originates in the municipality of Frasso Sabino (Rieti Province) mainly fed by the overflow of "Le Capore" Spring, that is tapped by the Peschiera Aqueduct, supplying above all the city of Rome (with about 4 m3/s). The Farfa River crosses a large part of the Sabina territory, between Rome and Rieti, within a wonderful example of north roman countryside. Here the water and history are deeply intertwined since Roman times, when Virgil in the Aeneid called the Farfa river as "Fabaris" and Ovid "Farfarus" in the Metamorphoses. Close to the river, near a spring which is named in the same way on the Latium Region hydrogeological map, the ancient Farfa Abbey was founded in the 6th Century. This place played a leading role, both religious and political, in many centuries of medieval history. The final stretch of the Farfa river (from Granica to the end) is part of the Nazzano-Tevere-Farfa Regional Nature Reserve, part of EU Natura 2000 network. Its flow has carved out, over hundreds of thousands years, geomorphological features such as the Natural Monument of the Farfa Gorges and the lost natural arch so called "Ponte Sfondato". This latter was formed during a river rectification process that led to the fossilization of a meander and the opening of the natural arch within the rock, then collapsed (Pantaloni & Console, 2019; Pantaloni et al., 2020). This area is a great example of hystory and nature interconnection, but poorly studied from a hydrogeological point of view. Along the river a strong groundwater-surface water interaction occurs and this study has the goal of enlighting this area and open a door to future in-depth studies.

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Investigating the sustainability of groundwater resources in the Friuli high plain: a modeling approach

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Keywords: groundwater modeling, hydrogeology, sustainable water resources.

The Friuli-Venezia Giulia Region hosts one of the largest hydrographic basins in Italy, composed of multiple layered confined aquifers in its lower plain and a thick phreatic aquifer in the upper plain. Groundwater in the Region is crucial, approximately 50,000 water wells serve the population for agricultural, industrial and drinking use. Monitoring of the upper plain phreatic aquifer highlights a water table decline rate of up to 10 cm per year, raising concerns about the status and future availability of water resources.This project focuses on the sustainable management of the groundwater resource in the Friuli High Plain, and the potential impact of climate change. The project is in its early stages. The first step involves the development of a geological model of the study area, built using stratigraphic data from approximately 1,500 wells surveyed in the Region. For this purpose, the Petrel software has been used which, through interpolation techniques and geostatistics, allows the creation of a cell-based geological model. The model extends vertically for the entire Plio-Quaternary sequence. Once the geological structure has been defined, the focus will shift to the creation of a groundwater numerical model to investigate how exploitation and climate change impact water resources. For this phase, MODFLOW 2005, will be employed in conjunction with the ModelMuse graphical interface. The hydrogeological model will allow the analysis of groundwater budgets under different future climate scenarios, evaluating how the system responds to extreme drought or wet periods.

Field monitoring and GIS-based water balance of major carbonate aquifers in the central Apennine

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Keywords: GIS, Apennine, water balance.

The maps of the hydrogeological units in the Central Apennines serve as a valuable resource for understanding groundwater circulation, managing water exploitation, and promoting sustainable water use. Data collected during the POA Acquacentro project enabled the update of existing hydrogeological maps for the Abruzzo Region, including those by Cassa per il Mezzogiorno – CASMEZ (1983), Boni et al. (1986), Regione Abruzzo – Piano di Tutela delle Acque (2008), and Desiderio et al. (2011).

Six carbonate aquifers, covering an area of approximately 2,800 km², were analyzed. From a hydrogeological perspective, these formations consist mainly of fractured and karstified limestones with high permeability, typically layering above nearly impermeable marl or clay layers. Limestone aquifers primarily discharge through basal springs, each with a minimum flow rate exceeding 50 L/s. These water sources are extensively used for drinking water, hydroelectric power generation, irrigation, and aquaculture.

Monitoring was conducted both seasonally and continuously: seasonal monitoring required at least four field campaigns per year, while continuous monitoring was carried out using permanent measuring stations.

Alongside field surveys, a monthly water balance was calculated for each aquifer over a six-year period (2018–2023). Precipitation and evapotranspiration were spatially interpolated using regression analysis. Inflows and outflows were entirely estimated within a QGIS environment, with maximum, minimum, and average values derived for each month.

The results of the fieldwork and water balance assessments were consolidated into six hydrogeological models, each representing spring discharge, groundwater flow directions, hydrogeological units, and water balance components, providing a comprehensive characterization of each aquifer system.

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Unlocking stable isotopes for PFAS compounds: a new CSIA method

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Keywords: stable isotopes, PFAS, environmental monitoring.

Per- and polyfluoroalkyl substances (PFAS) are a class of emerging contaminants that have raised public concern due to their persistence in the environment and adverse health effects. Their polar and non-volatile nature limits direct analysis by Gas Chromatography (GC), constraining the use of Compound-Specific Isotope Analysis (CSIA) via GC-Isotope Ratio Mass Spectrometry (IRMS), a powerful tool for tracking contaminant sources and fate.

To address this limitation, a derivatization strategy was applied to perfluorocarboxylic acids (PFCAs), a particularly concerning PFAS subclass frequently detected in environmental samples, enabling their analysis by GC-Combustion-IRMS (GC-C-IRMS). Perfluoroheptanoic acid (PFHpA), perfluorooctanoic acid (PFOA), and perfluorodecanoic acid (PFDA) were successfully analyzed, with measurement errors below 0.5 ‰, consistent with typical CSIA precision for common organic pollutants such as hydrocarbons and chlorinated solvents. Conversely, the method proved unsuitable for perfluorooctane sulfonate (PFOS), highlighting the need for alternative preparation or analytical approaches for this compound.

The method was further tested on real matrices such as rainwater and tap water, demonstrating applicability; although detection limits remain relatively high (starting from 50 µg/L), suitable preconcentration techniques can enable CSIA at environmentally relevant concentrations (ng/L range).

Additionally, elemental analysis IRMS (EA-IRMS) of various PFCAs from different manufacturers revealed carbon isotope differences up to 10 ‰, well above analytical uncertainty, confirming the potential of the approach for source attribution.

A second phase of the study is currently underway, involving field sampling in one of the most heavily PFAS-contaminated areas in Europe, the province of Vicenza (Italy). Four sampling points were selected along distinct hydrological and cardinal directions relative to the contamination source and the supposed plume of contamination. Furthermore, a comprehensive literature review supported the selection and setup of an improved analytical workflow, incorporating additional derivatization and solid-phase extraction (SPE) preconcentration, which is now being applied to the collected environmental samples.

This evolving approach offers a promising basis for developing a robust tool to trace and monitor PFCA contamination, supporting more effective management and remediation of PFAS pollution in complex environmental contexts.

Managing the ecological flow of rivers by an experimental integrated approach: results from the Umbria Region case study (Central Italy)

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Keywords: ecological flow, Umbria region, groundwater-surface water interactions.

The sustainable management of water resources requires the definition of the Ecological Flows of rivers (EF) to achieve the objectives defined by the Water Framework Directive (2000/60/EC). The groundwater availability in the Mediterranean Region has decreased in recent decades due to anthropogenic and climatic impacts (IPCC, 2023), affecting the river discharge. Considering the increase in withdrawals for different uses or river diversions for hydroelectric purposes, managing bodies in charge of issuing authorizations urgently need methods to sustainably define the EF values for preserving aquatic ecosystems, achieving a good status for groundwater and surface water bodies. The present study analyzes the different factors involving the river system (hydrologic, hydrobiological, hydrogeological, hydro-morphological, and hydrochemical) to develop an integrated approach for defining the EF in some river sections in the Umbria Region (Central Italy). Several river sections with catchments characterized by different hydrogeological characteristics (from high permeability limestones to medium-to-low fluvial lacustrine deposits) have been considered. The Ecological Status (i.e., the assessment of the quality of the structure and functioning of the surface water ecosystems) has been defined considering the New Index of the Ecological Status of Fish Communities (NISECI; Macchio et al., 2017) combined with the physicochemical characterization of river water as criteria for its definition. A geostatistical regional model developed for brown trout and Barbus tyberinus has been used to set the minimum EF in different river sections. Based on flow-duration curves, the maximum and average EF values were also identified; the latter has also been evaluated considering a new approach based on MQI (Morphological Quality Index; Rinaldi et al., 2013), channel-forming discharge, and mean discharge. Finally, the Water Exploitation Index Plus (WEI^+; Faergemann, 2012) has been used to identify well-localized areas at a higher risk of water drought and excessive water exploitation.

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Spatio-temporal evolution of pollutants in the groundwater systems of Vicenza province

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Keywords: geostatistic, groundwater pollution.

Groundwater is an essential freshwater source, facing threats from overexploitation and surface pollutants. Italy's largest freshwater reserve, the Po plain aquifer system, is both highly productive and vulnerable due to its peculiar setting, where the high, middle and low plain that can be recognised. In collaboration with Viacqua S.p.A., this study analyses pollutant concentration data collected from over 900 wells over the period between 1981 and 2023, assessing groundwater quality in Vicenza province. Specifically, the focus is given to the Agno Valley and the plain north of Vicenza municipality. Both areas have significant industrial and agricultural activities. The study examines spatio-temporal evolution of pollution plumes for PCE (perchloroethylene), TCE (trichloroethylene), nitrates, pesticides, sulphates, and chlorides. Three out of the five pollutants exceeded the legal concentration limits during the monitoring period, showing consistent patterns. Using statistical and geostatistical methods, particularly Ordinary Kriging interpolation, the research provides insights into space and time evolution of the groundwater quality and reveals key features of the hydrogeological setting and groundwater dynamics of the areas.

Ex-ante environmental assessment of groundwater pumping: application in the Rio Picocca plain (South-East Sardinia)

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Keywords: groundwater abstraction, environmental assessment, saline intrusion.

The EU Water Framework Directive (2000/60/EC) requires Member States to define environmental criteria for ex-ante assessments related to water abstraction requests. In line with this directive, the Italian Ministry of the Environment issued the STA Director Decree No. 29 of 13 February 2017 (DD 29/STA/2017), which introduced specific guidelines aimed at assisting authorities in applying the provisions of Royal Decree No. 1775 of 11 December 1933 concerning water abstractions.

Through a collaboration agreement between the University of Cagliari (DSCG), the Sardinian Hydrographic District Agency (ADIS), and the Regional Environmental Protection Agency (ARPAS), an analytical strategy was proposed for conducting ex-ante environmental evaluations of groundwater pumping. This method consists in forecasting the impacts that aquifer exploitation may cause by estimating both the intensity and spatial extent. Therefore, it is necessary to define the qualitative and quantitative status of the water body through piezometric surveys and chemical sampling. Finally, a classification must be assigned, which can be either “good” or “poor”.

The methodological approach has been developed and applied to a pilot site located in the Rio Picocca plain, within the Sarrabus-Gerrei region (South-East Sardinia), specifically in the San Priamo village, part of the municipality of San Vito (SU). The study area is characterized by three hydrogeological units: the first consists of slope deposits and Pleistocene alluvial sediments; the second is made up of Holocene alluvial deposits; and finally, there are typical lagoonal and marshland sediments found near the present-day coastline.

This region presents a complex scenario where intensive agricultural activities coexist with significant seasonal increases in water demand due to a fluctuating summer population. Such dynamics may threaten the hydrogeological balance of the plain and accelerate saline intrusion processes, compromising groundwater quality.

3D Airborne EM in an integrated geological-geophysical approach for groundwater exploration in mountain environments

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Keywords: AEM, 3D, integration.

Climate change poses a major threat to natural resources, especially water, leading to its recognition as a key priority in the 2030 Agenda's Sustainable Development Goals. Mountain regions are particularly vulnerable due to shifting precipitation patterns, rising temperatures, and altered hydrological cycles. An integrated geological and geophysical approach is here proposed with the main goal to identify groundwater systems in complex, tectonically deformed mountain terrains.

In this context, 3D geological models have become powerful tools for visualizing and understanding the geometry, distribution, and connectivity of rock volumes that host aquifer systems. Among available solutions, GeoModeller (Intrepid Geophysics) is particularly well suited for geologically complex and deformed terrains. This implicit 3D geomodelling software suite employs a potential field method for interpolation (Calcagno et al., 2008), making it ideal for managing different geological data. In such environments, Airborne EM (AEM) surveys are recommended for characterizing the subsurface with dense spatial coverage.

A key innovation in this work is the integration of the 3D geological model as a constraint in the 3D geophysical inversion of AEM data. The basal boundaries of modelled geological units are treated as resistivity barriers that separate distinct regions within the model. In the inversion process the constraints on the electrical properties can be broken at these boundaries, as well as along faults, allowing for sharper discontinuities at the interfaces. The rationale behind this rule is that adjacent geological formations often exhibit significantly different electrical properties due to variations in lithology, porosity, and water content. By allowing contrasts in electrical properties at geological boundaries, the model can better represent sharp geological transitions.

By combining 3D geological modelling with 3D AEM surveys, this integrated approach enhances subsurface imaging and reveals the distribution of geological formations, fault networks, and karst features that control groundwater flow and storage. The method has been tested in the Aracena case study (South of Spain), where an AEM survey was carried out with the Xcite system by NRG. Induced polarization was modelled as well using the Maximum Phase Angle model (Fiandaca et al., 2018), to account for the change of sign present in the AEM data, and the forward and Jacobian computations were carried out in 3D following Chen et al. (2024), to account for the rugged topography and the complex resistivity contrasts.

The geologically-informed 3D AEM modelling of the area produces results that closely match known geological features and facilitate easier model interpretation. The integrated geological-geophysical approach developed in this study enhances the understanding of groundwater systems in mountain terrains and supports the evaluation of their potential for sustainable water resource management.

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Potentially toxic elements and persistent organic pollutants in river sediments of Eastern Uzbekistan: sources and ecological and human health risk assessment

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Keywords: river sediments, inorganic and organic pollutants, water quality.

Sediments are a fundamental component of riverine environments and serve as key indicators for assessing pollution sources that may affect water quality. They act as long-term sinks for both natural and anthropogenic contaminants, including Potentially Toxic Elements (PTEs) and Persistent Organic Pollutants (POPs). Understanding their occurrence and distribution is essential for identifying pollution sources, monitoring long-term trends, and evaluating ecological risks.

In Central Asia, sediment monitoring is rarely conducted, despite increasing concerns about water use and environmental management. This study focuses on the Chirchik-Akhangaran Basin (CAB) in eastern Uzbekistan. As the most industrialized and densely populated region in the country, the CAB experiences significant environmental pressure, yet data on sediment contamination remains scarce. This research aims to characterize the spatial distribution of PTEs and POPs in river sediments, identify their potential sources, and assess ecological and human health risks using established sediment quality guidelines.

For organic pollutants, most concentrations were below the Threshold Effect Concentration (TEC) and national legal limits, indicating limited widespread pollution. However, elevated levels were observed at specific sites. Benzo[a]pyrene (BaP) exceeded both the TEC and the national limit of 20 µg/kg at sites AN-S2, AN-S5, CH-S6, and CH-S8. High concentrations of other PAHs, including BbF, BkF, IcdP, and BghiP, were also detected at these locations.

The site near the Angren coal-fired power plant recorded the highest total PAH concentration (ΣPAHs = 3876 µg/kg), pointing to industrial activity as a major source. Similarly, the site upstream of the Almalyk Mining and Metallurgical Complex showed elevated PAH levels, suggesting inputs from the metal industry.

PTEs contamination assessed using environmental indices indicated low to moderate levels for Li, Be, Co, Ni, Sb, V, and Cr in Chirchik-Akhangaran sediments. Some Akhangaran sites showed moderate to high contamination by Cu, Zn, Mo, Cd, Tl, Pb, and As. Ecological risk indices suggest low to moderate risk in most stations, with high risk confined to a few Akhangaran locations.

A human health risk assessment was also carried out for the Chirchik River, where recreational activities are common. Non-carcinogenic risks were within acceptable limits for all contaminants and exposure pathways. The cumulative Hazard Index (HI) was below the threshold (HI < 1) for both children (0.795) and adults (0.0927). However, the carcinogenic risk due to arsenic ingestion was deemed unacceptable; the screening level for As was calculated at 2.86 mg/kg.

These findings underscore the importance of risk assessment to identify threats to aquatic ecosystems and public health. The study highlights the need for continuous monitoring and effective management strategies to mitigate the impact of legacy and emerging contaminants in freshwater systems.

Assessing legacy and ongoing contamination in a coastal urban park: a hydrogeochemical study from Versilia (Italy)

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Keywords: urban parks, water-sediment-soil geochemistry, risk analysis.

This study investigates the geochemical characteristics of water, soil, and bed sediments in Versiliana Urban Park, on the coastal Versilia plain in Tuscany, Italy. The park is environmentally significant, hosting diverse vegetation and migratory birds. It lies within a tectonic basin filled with various sediments, shaped by deposition and hydraulic reclamation.

Two main canals cross the park, forming wetlands and interacting with the unconfined aquifer. These canals experience seawater intrusion, managed via floodgates and pumps. Groundwater levels respond to rainfall, and piezometric data show stable flow directions with three domes along sand dunes. Electrical conductivity indicates complex salinity patterns, especially in deeper groundwater.

The hydrochemical data indicates various groundwater types, influenced by processes such as mixing and cation exchange, as well as sulfate reduction and sulfide stability. Surface and canal water compositions vary seasonally, with salinization more evident during certain surveys. Pore water from the hyporheic zone reflects rising saline groundwater.

Most Potentially Toxic Elements (PTEs) concentrations in water are below regulatory limits, though As, Mn, and Fe exceed thresholds in some samples. Soil samples generally meet regulatory standards, except for elevated As and, in one case, high Zn, Sb, and Pb. Sediment analysis reveals exceedances of TEC and PEC thresholds for Ni, Cr, As, Zn, Pb, and Cd, indicating potential ecological risks.

Organic pesticide concentrations in sediments frequently exceed international sediment quality guidelines, particularly for DDT, DDE, DDD, heptachlor epoxide, chlordane, and endrin. The highest levels are typically found during the second survey, especially at stations SF1, SF2, SF3, and SF10. Certain pesticides and fungicides also reach concerning concentrations, with implications for sediment toxicity.

Arsenic in soil poses a long-term risk to groundwater through leaching. Calculated groundwater concentrations based on leaching models are below legal limits, but exposure pathway-specific soil screening levels (SSLs) for carcinogenic effects are exceeded in some cases. Overall, soil and bed sediments act as sinks for both PTEs and organic pollutants, influenced by local anthropogenic sources such as traffic, agriculture, and industry.

Elemental correlations point to both natural (e.g., ophiolite-derived Cr and Ni) and anthropogenic (e.g., As, Sb, Pb, Zn from mining areas) sources. The geoaccumulation index identifies sample PF-S4 as highly contaminated, suggesting a buried industrial source. Remediation is recommended for this hotspot, and moderate contamination by Se and As is noted elsewhere.

In conclusion, the study highlights the complex interactions between natural processes and human activities in shaping the geochemical landscape of urban green spaces. Ongoing monitoring and targeted remediation are crucial to safeguarding these valuable ecosystems.

Multiscale and multidisciplinary analysis of subsurface heterogeneity and its implications on contaminant transport: critical issues and perspectives for the design of the national repository of radioactive waste

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Keywords: groundwater hydrology, aquifer stratigraphy, geostatistics.

The design and implementation of radioactive waste disposal facilities (RWDF) require a comprehensive safety assessment that includes the evaluation of the potential dispersion of radioactive isotopes into the environment in the event of accidental leakage from engineered barriers. Many selected sites for the national RWDF, as well as existing temporary repositories for low- and intermediate-level radioactive waste, are located in regions characterized by thick alluvial deposits composed of fluvial and glacio-fluvial porous sediments. Consequently, ensuring long-term safety requires modeling groundwater flow and solute transport in these porous media at various scales: from the near-field, i.e., close to the point of release, to the far-field, extending further along the groundwater flow direction; from short times to times comparable to the service life of RWDF and to the half-time of stored radioisotopes.

Accurately predicting the fate of radioisotopes accidentally released from RWDF over different spatial and temporal scales necessitates an integrated approach, combining multiple disciplines such as hydrostratigraphy and aquifer sedimentology, hydrogeophysics, geostatistics, and physics of flow and transport in porous media.

The reliable mapping of the heterogeneity of physical parameters across a broad range of spatial and temporal scales, from nanometers to kilometers, from hours to centuries is the first challenge to be tackled. Real-world and aquifer-analogue studies on porous alluvial systems demonstrate that flow and transport paths and timing strongly depend on the geometrical relationship between the most permeable sediments and the intervening confining layers, together with the possible trapping of pollutants in low permeability structures and the successive slow, long-term release.

Adsorption/desorption phenomena occurring at the pore/grain scale take place under complex conditions, largely influenced by the mineralogy and petrography of sediments and the presence of competing chemical species in potential RWDF leachates. These processes are investigated through laboratory experiments on samples to determine the kinetic and equilibrium non-linear models for larger-scale mathematical modeling.

Moreover, robust assessment of uncertainty in model outcomes and forecast, due to the partial knowledge of the aforementioned processes and of the sediment heterogeneity, can be conducted in a Monte-Carlo framework, based on the geostatistical simulation of equiprobable multiple realizations, with methods going beyond the common two-point correlation paradigm.

Well-established numerical models of flow and transport in porous media should be adapted and tailored for a multiscale simulation of non-linear processes in heterogeneous porous media.

These crucial issues can be successfully solved only through multidisciplinary studies, an overview of which is presented here.

Hydrochemical characteristics and geochemical modelling of groundwater in the Pollino national park

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Keywords: geochemical modelling, environmental monitoring, spring water contamination analysis.

In the Basilicata region and in particular in the area of the Pollino Massif, southern Italy, the issue of natural-geogenic pollution has always had some attention.

Within this scenario was activated the regional project LucAs ("Lucania tra Ambiente e Salute"), focused on various environmental aspects, with health and epidemiological implications. These include the work package that investigates the distribution processes of elements of particular environmental interest, in the groundwater of an area selected in the Pollino Massif Geopark.

Trace elements in groundwater play a key role in determining water use because they can be derived from natural (geogenic) and/or anthropogenic sources.

This study focuses the distribution of trace elements, including some of major environmental interest (Cr, Fe, Ni, Pb, etc.) to start a geochemical survey which will lead to an assessment of the potential for natural contamination of spring waters in the northern sector of the Pollino massif (southern Apennines), specifically between the municipalities of Lauria and Castelluccio (PZ, Basilicata).

The study allowed the sampling of 26 sites, including springs and wells, respecting the protocol adopted by the laboratory of Environmental Geochemistry, University of Basilicata (UniBas).

Preliminary results were evaluated through conditional formatting in the Excel software and box-plot diagrams (box-plot), indicating the elements that exceed the limit provided by the regulations described in tables drawn up by APAT (Environmental Protection and Technical Services Agency), which compares the acceptable limit concentrations ex D.M. 471/99 and the contamination threshold concentrations ex D.Lgs 152/06 on groundwater.

In detail, we have been found 7 elements that, in some cases, exceed the maximum limit provided for by current legislation, namely Be, Al, Fe, Ni, As, Ag and Pb. Particular attention is given to iron (values reaching 2400 µg/ l, with a limit of 200 µg/ l), and lead (values up to 30 µg/l, with a limit of 10 µg/l).

Permeability mapping: from outcrop to basin model

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Keywords: permeability, mapping, Sardinia.

Understanding the permeability of rocks is essential for addressing groundwater resource concerns, as permeability—together with recharge rates and hydraulic gradients—controls the movement of water through aquifers (Gleeson et al., 2011). In sedimentary basins, the spatial distribution of permeability is particularly critical for interpreting fluid flow pathways, contaminant transport, and effective groundwater management (Huscroft et al., 2018). Since permeability is strongly influenced by lithology and petrophysical characteristics, vertical and lateral variations in rock types are key controls on its distribution.

To investigate these variations, we developed a surface permeability map of the Logudoro Basin in northern Sardinia. The study is based on an updated geological map and a balanced 3D geological model, which together provide a solid framework for the interpolation and extrapolation of field data. Lithostratigraphic units were characterized using in situ permeability measurements taken directly on outcrops with a portable air-permeameter (Tiny-Perm 3, New England Research, Inc.). This tool enabled rapid, cost-effective acquisition of air permeability data. These surface measurements were complemented by vertical permeability logs, allowing us to assess variations between lithostratigraphic units and heterogeneities within individual units caused by facies changes.

The analysis led to the classification of four primary surface permeability units based on lithological characteristics and corresponding permeability values: (1) Low-permeability volcanic basement; (2) Low-permeability sedimentary rocks; (3) Carbonate rocks with generally low matrix permeability, locally enhanced by fracturing; and (4) High-permeability sandstones. This integrated approach provides a clearer understanding of how geological structures and lithological changes control permeability at different scales. Looking ahead, the permeability map, vertical logs, and 3D geological model form a robust basis for constructing a comprehensive 3D permeability model of the basin. Future work will also focus on calibrating in situ air permeability measurements with hydraulic conductivities obtained from laboratory analyses, with particular attention to the specific lithologies present in the basin.

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Fontanili as sentinels of climate change – the Italian contribution in a pan-European study for spring assessment

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Keywords: fontanili, climate change, ecosystem.

Springs are the critical interface between groundwater and surface ecosystems, playing an essential role in sustaining biodiversity. However, they remain underrepresented in European water management policies. The European project SentinelSpringS addresses this gap by establishing a harmonised framework for assessing spring health across diverse landscapes. Within this multinational effort, the Italian research team focuses on lowland springs (*fontanili*), which are particularly vulnerable to climate change and anthropogenic pressures due to their location in densely populated and intensively cultivated areas.

The Italian case study employs a multidisciplinary monitoring strategy of *fontanili* in two pilot areas of the Piedmont Po Plain (Turin and Vercelli plains). The objective is to integrate hydrogeological and ecological indicators to evaluate the health and the impacts of climate change on these spring systems. The approach includes high-frequency monitoring of hydrological parameters (e.g. spring discharge and groundwater level), water quality (e.g. pH, EC, major ions), and biotic components (encompasses macroinvertebrate assemblages and aquatic vegetation), aiming to define reference conditions and identify early warning signals of environmental stress.

The Italian case study will contribute, together with case studies from other five European countries, to the design and testing of a unified spring typology and monitoring protocol to be adopted across Europe. Moreover, data generated will feed into broader EU-level analyses and support the development of adaptive management tools (Hinsby et al., 2025).

Through this work, Italy contributes to shaping a pan-European model for spring assessment, while offering site-specific insights into the sustainability of groundwater-dependent ecosystems. The outcomes will support evidence-based water governance and help protect these often-overlooked yet ecologically vital freshwater resources.

Acknowledgments: The project SentinelSprings has received national funding from Fundação para a Ciência e a Tecnologia-I.P. (FCT-Portugal), Agence Nationale de la Recherche (ANR-France), Ministero dell'Università e della Ricerca (MUR-Italy), Narodowe Centrum Badań i Rozwoju (Poland), Innovation Fund Denmark (Denmark), Ministry for the Environment, Energy and Public Cleansing (MEEC-Malta) and the European Union's Horizon Europe Programme under the 2023 Joint Transnational Call of the European Partnership Water4All (Grant Agreement n°101060874).

Hinsby K. et al. (2025) - Towards a Digital Information Platform for Locating and Assessing Environmental Impacts of Submarine Groundwater Discharge: Examples from the Baltic Sea. J. Mar. Sci. Eng., 13, 614, https://doi.org/10.3390/jmse13030614.

Stratigraphic and hydrogeological setting of river Secchia alluvial deposits (Emilia Romagna - Northern Italy) for Managed Aquifer Recharge.

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Keywords: Managed Aquifer Recharge, Quaternary alluvial deposits, groundwater.

Managed Aquifer Recharge (MAR) is the controlled infiltration of water into underground aquifers, either for recovery or to achieve environmental benefits (Dillon et al., 2022*)*. Different nations use MAR as an essential tool to mitigate the climate change effects. For instance, infiltration ponds can both aid in replenishing depleted aquifers, thus alleviating the impacts of severe drought and overexploitation of groundwater resources and reduce flooding risks when used as flood retention basins. Gravelly deposits at the outlet of mountain valleys are the best suited for MAR, thanks to high infiltration rate (Meles et al., 2024). In this study, we reconstructed alluvial stratigraphy along the Secchia River, at the transition between the uplifting Apennines and the subsiding Po Plain, in northern Italy. This research aims to characterize the Secchia River alluvial deposits from stratigraphic and hydrogeological perspectives to identify suitable sites for developing infiltration pond MAR in existing quarries. Subsurface stratigraphy was reconstructed by correlating outcrops, boreholes, and water-well data down to 350 m depth. The Secchia deposits show a cyclic pattern of gravel banks and mud layers. The latter increases in the thickness distally, while gravel bodies show a parallel decrease in thickness and degree of interconnection. The gravel banks consist of poorly sorted clast-supported gravels, with clasts ranging in size from a few centimeters to half a meter, usually imbricated. Within individual gravel bodies, lenticular units, a few meters wide, are bounded by concave erosional surfaces. These features are typically associated with braided river deposition. Gravel bodies are capped by rubified paleosols, up to one meter thick, with altered clasts, due to iron (Fe) and manganese (Mn) oxides and hydroxides, and argillic horizons rich in carbonate concretions. Mud horizons with thin pebble layers, are yellowish with carbonate concretions. Locally, mud shows lateral transition to lens-shaped gravel to sand bodies, with a fining upward trend and epsilon bedding. Those coarse-grained sediment bodies are interpreted as in meandering fluvial systems, while fine sediments testify to overbank deposition. Gravel bodies represent efficient groundwater reservoirs, while muddy horizons and paleosols may act as a hydraulic barrier to fluid circulating in the subsurface. For each gravel body, a hydraulic conductivity value is determined utilizing well tests and bibliographical data, developing a conceptual hydrogeological model. Furthermore, a water depth map, reconstructed using decades-long well and piezometer data monitored by ARPA Emilia Romagna, allowed to understand the relationship between the river and the water table. The creation of a detailed 3D stratigraphic model will support the hydrogeological modelling with the final aim of analyzing suitable quarries for infiltration pod MAR.

Dillon et al. (2022) - Managed Aquifer Recharge: Overview and Governance. IAH Special Publication, https://recharge.iah.org/ ISBN 978-1-3999-2814-4.

Meles M. et al. (2024) - Uncovering the gaps in managed aquifer recharge for sustainable groundwater management: A focus on hillslopes and mountains. J. Hydrol., 639, 131615, https://doi.org/10.1016/j.jhydrol.2024.131615.

Antimony accumulation and rhizosphere mineralogy of *Dittrichia viscosa* at a contaminated Sb abandoned mine site

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Keywords: antimony, phytoremediation, *Dittrichia viscosa*.

Antimony (Sb) is recognized by the European Union as a Critical Raw Material (CRM) due to its strategic economic role and limited global availability. Predominantly released through mining activities, Sb can contaminate soil and water, posing serious environmental and public health threats. Due to its toxicity, the U.S. Environmental Protection Agency identifies Sb as a priority pollutant (Bagherifam et al., 2019).

Phytoremediation, using plants to stabilize, remove, or degrade environmental contaminants, offers a promising solution for mitigating Sb pollution. This approach exploits plant-based mechanisms such as phytoextraction, phytostabilization, and phytotransformation to reduce contaminant mobility and bioavailability (Moreira et al., 2021).

Dittrichia viscosa, a resilient perennial species, has been identified as a potential plant species for phytoremediation applications (Barbafieri et al., 2011). A preliminary field study was carried out at the Su Suergiu abandoned mine site in southeastern Sardinia, Italy (Fancello et al., 2023), focusing on *D. viscosa* growing both on the mine dump (mine wastes and foundry slags) and along the slag drainages. The rhizosphere (the soil in the range of 1-5 mm from the roots) showed Sb concentrations as high as 8% and up to 1% in samples collected from the mine dump and along slag drainages, respectively. Sb levels in plant tissues ranged from 520–5500 ppm in roots, 50–440 ppm in stems, and 140–880 ppm in leaves. Interestingly, roots from plants along the drainage area exhibited higher Sb accumulation than those from the mine dump, likely reflecting a greater Sb bioavailability in water, where concentrations reached up to 103 ppb.

Mineralogical analyses revealed that the rhizosphere was dominated by quartz and calcite, with minor phyllosilicates, likely illite and muscovite. Notably, mopungite [$NaSb(OH)_6$], an Sb-bearing mineral, was identified in the samples from the mine waste and observed in direct association with root surfaces by Scanning Electron Microscopy.

These preliminary findings highlight the capacity of *D. viscosa* to tolerate and accumulate significant Sb concentrations. The presence of mopungite in the rhizosphere and on roots suggest an active plant-mediated stabilization or transformation of Sb species. This research reinforces *D. viscosa* potential in Sb phytoremediation and highlights the critical role of mineralogical and geochemical context in evaluating and optimizing phytoremediation strategies. Further investigations are essential to elucidate the processes driving Sb speciation and transformation, which are fundamental to improving remediation outcomes for Sb-contaminated environments.

Acknowledgments: The research was founded by PRIN-PNRR2022 (MOLIERE - antiMony resOurce itaLy environmental Exploration cRitical material).

Bagherifam S. et al. (2019) - Derivation methods of soils, water and sediments toxicity guidelines: A brief review with a focus on antimony. J. Geochem. Explor., 205, 106348, https://doi.org/10.1016/j.gexplo.2019.106348.

Barbafieri M. et al. (2011) - Uptake of Heavy Metals by Native Species Growing in a Mining Area in Sardinia, Italy: Discovering Native Flora for Phytoremediation. Int. J. Phytoremediation, 13(10), 985-997, https://doi.org/10.1080/15226514.2010.549858.

Fancello D. et al. (2023) - Antimony contamination sources and alteration pathways of Sb mineral phases in an abandoned mining area: The role of secondary mopungite [NaSb(OH)6]. Appl. Geochem., 156, 105764, https://doi.org/10.1016/j.apgeochem.2023.105764

Moreira H. et al. (2021) - Phytomanagement of Metal(loid)-Contaminated Soils: Options, Efficiency and Value. Front. Environ. Sci., 9, 661423, https://doi.org/10.3389/fenvs.2021.661423.

Monitoring the impact of aquifer salinization on coastal vegetation using remote sensing: the case of the Emilia Romagna coast

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Keywords: normalized difference vegetation index, coastal aquifer, salinization, remote sensing.

The coastal aquifer of Emilia Romagna is naturally prone to saltwater intrusion, which threatens the water resource and the fragile ecosystems along the coast. This vulnerability is caused by several factors such as land subsidence, urbanization, drainage activities, and unsustainable water use during the dry summer months, making seawater intrusion a significant risk for the groundwater system in this area. The study focuses on assessing groundwater salinity changes in the Emilia Romagna coastal aquifer from 2009 to 2023 by analyzing data from 35 piezometers distributed across the regional coastal area. It examines trends in rainfall, groundwater levels, and electrical conductivity, and creates maps to visualize the evolution of salinity and water table level. Additionally, the study explores the relationship between salinity increases and vegetation stress, ultimately proposing remote sensing methods to improve monitoring and promote sustainable water resource management. No significant trends were observed in regional precipitation, suggesting that salinity changes in the aquifer are more closely tied to local hydrogeological factors and water management. Surface water and groundwater salinization are enhanced along the surface water bodies connected to the sea and in the areas with sandy sediments near the coast and rivers. Freshwater lenses persist within paleodunes, acting as natural barriers against salinity, though these lenses are vulnerable to irrigation practices and water use during dry periods. The lowest water table level occurs in the western and northern parts of the study area, because of the semiconfined behavior of the aquifer. Vegetation health, assessed via the NDVI index, varied with proximity to saline water. Coastal pine forests and heathland vegetation exhibited resilience to moderate salinity levels, likely due to species-specific adaptations. However, increased salinity correlated with a decline in vegetation health in agricultural zones, reflecting salt stress conditions. The findings show that while native vegetation in coastal ecosystems shows some tolerance, salinity poses a significant threat to agricultural productivity and ecological balance, especially under climate change. This study supports the need for ongoing monitoring and adaptive management to mitigate salinization impacts.

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Impact of climate-driven inundation and drought cycles on toxic elements release from legacy coastal wastes in the United Kingdom

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Keywords: mesocosm experiment, leaching, contaminant hydrology.

Climate change is expected to affect the release of toxic elements from legacy waste landfills across coastal areas because it will enhance severe flooding, erosion, and extreme wetting-drying cycles. The UK's industrial past resulted in a wide range of legacy wastes deposited in estuarine and coastal settings, for a total of 3219 sites. A mesocosm experiment was carried out to investigate the leaching processes that can occur in different types of legacy waste (LW) disposed across the UK coasts. The experiment was designed to study how wetting and drying cycles affect the release of pollutants in the coastal areas. Four different types of LW were selected: colliery (L), landfill municipal wastes (CB), non-ferrous slag smelter (CP), and mining impacted sediments (HE). These four types represent the range of LW geochemistry encountered across the UK. A set of columns (*wd*) for each waste type underwent cycles of wetting/drying conditions. Control columns (*ctr*) were also designed to study the effect of constant inundation for each LW type. Artificial rainwater was used to inundate the columns. Water samples were collected for DOC, major ions and metals. Waste geochemistry and mineralogy were analyzed before the experiment.

Sulfur and carbon speciation analysis showed that S is mostly found as sulfide, especially in the L and CP wastes. The CB and HE samples showed the highest total C concentrations; the latter showed the highest inorganic carbon due its calcite content. L wastes showed the highest organic carbon content, followed by CB. L leachates were the most acidic (pH = 3.3 – 5.1), the other sites had pH ranging from 6.0 to 8.7. HE samples showed the largest variation range for EC and DOC (409 – 109000 µS/cm and 8.3 – 405.8 mg/l, respectively). The maximum variation for EC and pH occurred after the first *wd* cycle for all the sites but CP. For each site, *ctr* leachates showed wider ranges of variation than the *wd* ones. CP wastes released the lowest amounts of pollutants. L leachates showed the highest median concentrations for Ni, Co, Zn, and Cd among the four LW types. L wastes released the highest contents of Zn (*wd* = 1232105 µg/l, *ctr* = 1161220 µg/l) and Ni (*wd* = 13490 µg/l, *ctr* = 14052 µg/l). HE leachates showed the highest median concentrations of Cu (*wd* = 977.9 µg/l, *ctr* = 2133.8 µg/l) and As (*wd* = 125.5 µg/l, *ctr* = 141.2 µg/l). CB leachates had the highest median concentrations of Pb (*wd* = 50.1 µg/l, *ctr* = 53.8 µg/l). CB released up to 698.2 µg/l of Zn, especially from the *ctr* columns. On average, the control columns (*ctr*) released more toxic elements than the wet/dry ones (*wd*), regardless of LW type.

It appears that leaching processes are more likely to be efficient at the end of prolonged dry periods when heavy storms occur and saturation conditions occur. Extreme climate conditions are expected to become more frequent in the near future, therefore proper management is mandatory to reduce the risk posed by the coastal legacy wastes.

Hydro-meteorological control on mercury transport across a mine-polluted fluvial system of the Monte Amiata mining district (Southern Tuscany, Italy)

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Keywords: mine wastes, contaminant hydrology, Hg flux.

Mining activities may have a severe impact on fluvial systems due to the dispersion of huge amounts of heavily polluted mining wastes. Pollutants distribution in fluvial systems is controlled by the interplay between weather conditions, geomorphic processes, and anthropic activities. Mercury (Hg) is highly toxic and persistent in the environment. Hg mining is now limited to a few countries, but legacy mine wastes are still releasing Hg into the environment, particularly to fluvial systems. The Monte Amiata Mining District (MAMD, Southern Tuscany) was the 3rd largest Hg producer worldwide. The Paglia River (PR) basin drains the southeaster sector of the MAMD, covering an area of 1320 km^2. Previous studies estimated an Hg flux of 0.01 t/y from the PR to the Tiber River, but this value was based on spot samplings. In this study, the relationship between particle-bound Hg (Hg_p), total suspended solids (TSS) and water turbidity (Tb_w) for PR was investigated to calculate Hg fluxes from TSS and Tb_w monitoring. Water samples were collected in different hydrological conditions between 2022 and 2025. Samples were collected along the PR, upstream and downstream of the Elvella creek confluence (ECC), a non-polluted tributary, to evaluate its effects on the Hg budget. The samples were filtered and the TSS collected on the filters were analyzed for Hg and Tb_w. TSS ranged between 1.3 and 1475.7 mg/L, whereas Hg varied between 0.8 and 667.2 ng/L. Tb_w varied between 12.2 and > 1100 NTU and a linear relationship was found between TSS and Tb_w. The highest Hg and TSS values were measured during the recession phase of major flooding events, whereas the lowest ones were found during low flow conditions. A linear relationship was also found between Hg and TSS. Hg was higher in the upstream samples than in those collected downstream the ECC, confirming that Hg source is the heavily mine-polluted PR catchment. Yearly Hg fluxes were estimated to be comprised between 0.02 and 0.16 t/y, (mean = 0.09 t/y). This study demonstrated that the Hg delivery from the PR to the Tiber River, and ultimately to the Mediterranean Sea, is higher than previously expected. Moreover, the intensity of precipitation is the principal forcing factor on the Hg release. This is a critical aspect because climate change is expected to affect rainfall intensity, with yearly precipitation progressively distributed over few and intense storm events. Additionally, the relationship between Hg and TSS could be applied to the indirect, continuous measurement of Hg fluxes discharged by PR with an automated TSS/Tbw sensor. Such monitoring would allow a real time assessment of the Hg pollution in the PR basin in case of flooding.

Infitration driven transport of quarry suspended material in the karst aquifers of the Apuan Alps (Tuscany, Italy)

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Keywords: groundwater, karst aquifer, physical pollution.

This study inserts into a joint research initiative between ARPA Toscana and the Department of Earth Sciences, University of Florence to assess the impact of marble quarrying activities on groundwater resources in the Apuan Alps. The present project builds on a previous research (Nannoni et al., 2021) and investigates the transport dynamics of marble-cutting wastes, locally known as "*marmettola*" (mainly $CaCO_3$), by infiltration water within karst systems. These residues, present as fine powder or slurry, infiltrate through fractures and conduits and reach groundwater in suspension, eventually emerging at karst springs as turbidity. The main goal is to assess how *marmettola* moves through subterranean networks (along karst pathways such as fractures and conduits) and impacts groundwater quality, particularly during flooding events when turbidity peaks occur.

The first phase of the investigation involves a detailed analysis of the monitoring data collected by ARPAT from 2019 to 2024 in some of the main karst springs in the Apuan Alps. The main monitored springs are: Equi Terme, Forno (Frigido), Cartaro, Carbonera, and Tana dei Tufi, along with the major underground river within the Monte Corchia karst system. The ARPAT monitoring data (available online at https://sira.arpat.toscana.it) are recorded hourly and include the following parameters: water level, turbidity (expressed in NTU – Nephelometric Turbidity Units – with a variable end-scale ranging from 330 to 440 NTU), temperature (°C), and specific electrical conductivity (µS/cm at 25 °C).

Turbidity events were classified using arbitrarily defined NTU thresholds (10 ≤NTU<50, 50 ≤NTU<100, 100 ≤NTU<300, 300 ≤NTU), allowing for cross-site comparisons and temporal analysis. Preliminary results show that Cartaro is the spring that most frequently exceeded the 300 NTU threshold during the monitored years (between 20 and 30 events per year), whereas the other springs generally recorded fewer than 10 such events annually. Although turbidity is associated with flood events, which in turn depend on precipitation, a direct correlation between total rainfall and the number of turbidity threshold events is not clearly evident. Major turbidity events occur during or a few days after strongest rainstorms but turbidity can easily exceed 100 NTU also during low discharge phases, testiphying a direct connection between quarry sites and springs.

For Equi Terme and Frigido, where discharge data (m^3/s) are available, NTU values were converted to transported mass (kg) using the relationship found by Drysdale et al. (2001). Results have shown that up to ~1000 kg of *marmettola* during 2019 reached the spring of Equi Terme (lower values have been found for the following years), while for Frigido spring the maximum value found was ~250 kg in 2021.

The second phase of the project involves SEM (Scanning Electron Microscope) analysis of sediments from springs and caves to distinguish natural materials from antropogenic ones. The project also includes GIS-based integration of data to support further hydrogeological evaluations.

Drysdale R. et al. (2001) - Suspended sediments in karst spring waters near Massa (Tuscany), Italy. Environ. Geol., 40, 1037-1050, https://doi.org/10.1007/s002540100311.

Nannoni A. et al. (2021) - Innovative Approaches for the Sedimentological Characterization of Fine Natural and Anthropogenic Sediments in Karst Systems: The Case of the Apuan Alps (Central Italy). Front. Earth Sci., 9, 672962, https://doi.org/10.3389/feart.2021.672962.

Use of minor and trace elements for identification of a coastal aquifer flow path

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Keywords: minor and tracer element.

Minor and trace element geochemistry, along with strontium isotopes in groundwater, was investigated in this study with two primary objectives: (I) to delineate groundwater flow paths within a coastal aquifer system and (II) to evaluate impact of former mining activities on groundwater quality. The study area is located in the Flumendosa Plain, on the southeastern coast of Sardinia. The plain area is primarily composed of Holocene alluvial deposits related to the recent depositional dynamic of the Flumendosa River. Pleistocene alluvial fan deposits, characterized by lower permeability, are widely exposed along the margin of the plain, particularly to the south, and in the piedmont areas of the main tributary valleys (e.g., Riu Pibilia, Flumini Uri). The surrounding hilly terrain is mainly composed of low-grade metamorphic rocks belonging to the Paleozoic basement of Sardinia. These rocks include sedimentary and volcano-sedimentary sequences that were metamorphosed to greenschist facies, dating from the Middle Cambrian to the lower Carboniferous (Carmignani et al., 2001). The alluvial aquifer is currently affected by overexploitation and significant seawater intrusion. Moreover, several former mining sites are located in the hills surrounding the plain, where mine workings and waste deposits interact with surface and groundwater flowing towards the plain (Cidu et al., 2008).

A comprehensive set of major, minor, and trace elements was analysed in both groundwater and surface water samples and combined with strontium isotopes only in groundwater. Geochemical data were corrected for salinity contributions resulting from seawater mixing. The integration of these data with strontium isotope ratios enlightened the relative contributions of the Flumendosa and Flumini Uri to the aquifer. Furthermore, groundwater analyses revealed concentrations exceeding regulatory limits for Fe, Mn, Sb, and F, along with elevated levels of Cu, Co, Zn, Pb, Ni, and U. These findings exhibit a correlation with the substantial mineralisation present within the Palaeozoic basement. This correlation is further supported by the spatial distribution of these elevated concentrations, predominantly observed in groundwater samples located near bedrock exposures or watercourses receiving mine drainage.

Carmignani L. et al. (2001) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000 - F.549 Muravera.

Cidu R. et al. (2007) - Caratterizzazione idrogeochimica ed isotopica e valutazione della qualità delle acque superficiali e sotterranee campionate nel Foglio 549 Muravera. In: Ottonello G., ed., Geochemical baselines of Italy.

Perfluoroalkyl substances (PFAS) in freshwater in the Turin Metropolitan Area (Italy): Sources and compliance with water quality standards

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Keywords: PFAS, freshwater, Turin.

Perfluoroalkyl substances (PFASs) are synthetic, toxic, polluting and astoundingly recalcitrant molecules. Arpa Piemonte has been monitoring a total of 19 different PFASs in freshwater in the Piedmont region since 2021. Here, we report PFAS data from shallow (unconfined aquifers; 72) and deep (semi- and confined aquifers; 55) wells, streams (28) and 1 lake in the Turin Metropolitan Area collected in the 2021-2023 period (Randazzo et al., 2025). The aims of this study were to: (i) investigate the occurrence of PFASs in freshwater with respect to Italian and European environmental/drinking water quality standards; (ii) examine the contribution of potential point PFAS source categories (i.e., contaminated and reclaimed sites, industries, landfills and wastewater treatment plants); (iii) quantify the PFAS load in running streams in the area.

PFASs, varying in composition with water samples with no clear spatial and temporal trend, were revealed in 29 and 24 % of the investigated shallow and deep wells with a total concentration, as a sum (ΣPFASs), of 0.01–0.71 and 0.01–0.16 µg/L, respectively. The PFAS occurrence in shallow groundwaters appeared more related to (potentially-) contaminated and reclaimed areas, landfills and waste management plants rather than plants subjected to integrated environmental authorisations and wastewater treatment plants. Overall, PFAS occurrences increased with the degree of industrialisation and urbanisation in both unconfined and (semi-) confined aquifers. Exceedances in the environmental and drinking water quality standards/recommendations for PFASs occurred to a greater extent in shallow wells than deep wells.

PFASs were found in 96 % of the sampling sites in streams with ΣPFASs values of 0.0002–0.47 µg/L, whilst they do not occur in the investigated lake. A slight correlation was found between wastewater treatment plants and the occurrence of PFASs in streams. The annual ΣPFASs loads downstream of the Turin metropolitan Area were estimated around 150–220 kg. Exceedances in the AA-EQSs (Annual Average - Environmental Quality Standard) values were revealed only for PFOS, whilst thresholds for the other species were largely complied.

Exceedances in the PFASs' European and Italian guidelines occurring in both groundwater and surface water, claim for strong actions in safeguarding the quality of freshwater. However, the current PFASs' guidelines appear not to exhaustively cover the ever-increasing number of PFAS species and, consequently, are unable to protect aquatic systems fully. Accordingly, an in-depth revision and update of the guidelines is needed.

Randazzo A. et al. (2025) - Perfluoroalkyl substances (PFASs) in groundwater and surface water in the Turin metropolitan area (Italy): An attempt to unravel potential point sources and compliance with environmental/drinking water quality standards. Sci. Total Environ., 958, 177973, https://doi.org/10.1016/j.scitotenv.2024.177973.

Integrated analysis of the hydrodynamic behavior of the unconfined aquifer and soil moisture through satellite observations in an irrigated alluvial plain: eastern sector of the Po Valley, Italy

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Keywords: unconfined aquifer, soil moisture, Po plain.

Climate change and agricultural pressure are imposing significant stress on water resources, exacerbating the challenges of managing these resources sustainably. To achieve sustainable water management, an integrated and holistic approach is required, one that takes into account both temporal and spatial variability. Key factors include: a) soil moisture, a critical component in hydrological and biogeochemical processes. Variations in soil moisture affect water availability for vegetation, influence evapotranspiration rates, and modulate nutrient cycling, all of which are essential for ecosystem services and agricultural productivity; b) shallow aquifer, as it is often in direct contact with vegetation and agricultural activities. Groundwater dynamics, including recharge rates and storage, are critical for long-term water security and require detailed monitoring and modeling to inform sustainable management practices.

Given the interconnectedness of soil moisture and groundwater systems with climate, agricultural practices, and hydrological cycles, understanding these interactions is pivotal for developing adaptive strategies in response to both climatic variability and anthropogenic pressures.

In this context, the present study — carried out within the framework of the bePrepARed project — conducts an assessment of soil moisture and groundwater levels in the eastern sector of the Po Plain (Northern Italy). This area is characterized by intensive agricultural activity and, from a lithological point of view, is covered by alluvial deposits from the Po River and Apennine rivers, coastal and lagoon deposits, and includes extensive wetlands.

Specifically, the study was structured into the following phases:

a) soils were classified into four categories based on USDA soil texture classes from the Soil Map of Emilia-Romagna (1:50,000 scale), and using formation permeability as the grouping criterion;
b) daily climate data for the period 2015–2020 were analyzed (Boogaard et al., 2020);
c) the hydrodynamic behavior of the unconfined aquifer was evaluated through the analysis of time series data from a network of 40 piezometers (FaldaNet database) well distributed throughout the study area for the 2015–2020 period;

Boogaard H. et al. (2020) - Agrometeorological indicators from 1979 to present derived from reanalysis. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), https://doi.org/10.24381/cds.6c68c9bb.

The critical role of hydrogeological assessment in the sustainable development of shallow geothermal energy systems

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Keywords: hydrogeological assessment, distributed fibre-optic temperature sensing, shallow geothermal energy.

Climate change, the spread of atmospheric micropollutants, and the pressing requirements of European energy and environmental policies are key drivers behind the growing interest in renewable and eco-sustainable energy resources. Among these, shallow geothermal energy stands out as a viable solution for supporting the energy transition. However, the design and optimization of geothermal exchange systems demand a holistic and interdisciplinary approach that considers both the energy requirements of the built environment and the complex subsurface characteristics, including hydrogeological, chemical, and thermophysical properties, as well as legislative and environmental constraints.

In this framework, at a pilot site located in the alluvial plain of the Po River (northern Italy), the following investigations were carried out:

a) *sedimentological and grain size analyses*: continuous core drilling enabled the reconstruction of local sedimentary successions and the identification of aquifer systems;

b) *hydrogeological characterization*: by means of pumping tests and hydrodynamic monitoring, a local conceptual hydrogeological model was developed, providing insights into subsurface flow dynamics and their interaction with thermal gradients;

c) *hydrochemical and isotopic investigation:* groundwater samples were analyzed for major dissolved ions and isotopic tracers ($\delta^{18}O$, $\delta^{2}H$, $^{87}Sr/^{86}Sr$), offering valuable information on aquifer recharge processes and mixing phenomena between waters of different origins;

d) *thermo-physical properties and thermal response tests*: a monitoring system based on Distributed Fibre-Optic Temperature Sensing (DTS) was installed to continuously measure subsurface temperature profiles under both natural and operational conditions; in addition, Distributed Thermal Response Tests (DTRT) were conducted, supported by laboratory measurements of the thermal conductivity of subsurface materials.

The integrated analysis of the collected data enabled a robust hydrodynamic and thermo-physical characterization of the subsurface and informed the selection of a sustainable geothermal system. Finally, the data were used to calibrate predictive numerical models designed to simulate the subsurface's behavior under the thermal loads expected from a low-enthalpy geothermal plant.

Hydrogeological role of deep-seated gravitational slope deformations in the Northern Apennines: insights from preliminary data

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Keywords: DSGSD, hydrogeological controls, water circulation.

The Northern Apennines feature geological sequences marked by strong rheological contrasts, where fractured lithoid blocks (aquifers) overlie plastic clay-rich substrates (aquitards). This configuration fosters the widespread development of Deep-Seated Gravitational Slope Deformations (DSGSDs), which, while well documented in terms of geomorphological impact, are less understood in their hydrogeological role. This research aims at investigating how DSGSDs influence groundwater flow and the emergence of high-discharge springs, which are critical water resources in mountain environments.

Studies from Alpine and Apennine regions suggest that DSGSDs can significantly alter groundwater circulation by enhancing secondary permeability through deformation-induced fracturing. In the Rodoretto Valley (NW Alps), for example, such fracturing was shown to direct groundwater toward major springs (Gizzi et al., 2020). Similarly, the Montellina Spring (NW Italy) demonstrated deep, complex groundwater flow paths within a DSGSD (De Luca et al., 2019), while studies in Tyrol (Austria) highlighted the role of active DSGSDs in modulating spring dynamics and seasonality (Pfeiffer et al., 2022). Finally (Binet et al., 2007), uses the hydrogeological mapping and hydrochemical characteristics of natural spring waters to determine the relationships between groundwater and gravitational instabilities in the Upper Tinée Valley (South-East French Alps).

Preliminary results from our large-scale analysis of landslide and spring databases, integrated with field investigations along the Northern Apennine chain, reveal a strong spatial correlation between DSGSDs and high-yield springs. These springs — vital for domestic and agricultural use — tend to occur within or near DSGSD-affected zones, suggesting that gravitational deformations locally enhance aquifer permeability and facilitate focused groundwater discharge.

This emerging pattern contrasts with the region's typical diffuse spring regime, characterized by numerous low-discharge sources. Initial hydrogeological surveys from selected case studies further support the hypothesis that DSGSDs act as preferential flow structures, concentrating and sustaining groundwater discharge.

Building on these findings, the research aims to develop a standardized methodology for identifying and evaluating water resources linked to DSGSDs, with potential applications across other mountainous regions with similar geological frameworks. Ultimately, the project contributes to the strategic identification of resilient water sources—an increasingly urgent priority amid rising pressures from climate change and drought.

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Comparison of electrical resistivity tomography and frequency domain electromagnetic methods for mapping seawater intrusion in shallow aquifers

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Keywords: seawater intrusion, geophysics, coastal aquifers.

Seawater intrusion into coastal aquifers is an increasingly critical global issue, exacerbated by climate change, rising sea levels, and overexploitation of groundwater. Effective monitoring and assessment tools are crucial to ensure the long-term sustainability of freshwater resources. While conventional hydrogeological techniques such as borehole logging and Electrical Resistivity Tomography (ERT) provide detailed subsurface data, they are often constrained by limited spatial coverage and labor-intensive acquisition due to the need for direct ground contact. This study explores the use of Frequency Domain Electromagnetic (FDEM) methods as a rapid, non-invasive alternative for identifying shallow seawater intrusion. Field measurements were carried out at four distinct coastal sites in the Friuli Venezia Giulia region (N-E Italy), each presenting unique salinity gradients, geological settings, and seasonal variations. Two FDEM instruments were tested: a multi-offset, constant-frequency device and a single-offset, multi-frequency system, both selected for their ability to efficiently acquire broad, spatially continuous datasets. ERT was used as the reference technique for evaluating subsurface conductivity. Apparent electrical conductivity (ECa) values from FDEM surveys were normalized and statistically compared with ERT-derived data to assess accuracy and correlation. Although differences in absolute conductivity values were observed between the FDEM devices and the ERT profiles, the overall spatial trends in salinity distribution were consistent. Statistical calibration via cross-plot analysis significantly improved data alignment, though the effectiveness of such remained site- and season-dependent. The results demonstrate that, when appropriately calibrated, FDEM systems can reliably map shallow salinity distributions and are well-suited for extended survey areas and three-dimensional investigations. While ERT continues to serve as a powerful tool for localized, high-resolution studies, FDEM offers a faster and more practical solution for large-scale monitoring. Furthermore, this calibration approach is adaptable to a wide range of geological and environmental applications beyond hydrogeological studies. In summary, the integration of ERT and FDEM methods advances our capacity to monitor coastal aquifer salinization and supports the design of efficient, wide-area assessment strategies essential for sustainable groundwater management in at-risk coastal environments.

Integration of hydrogeochemistry, stable isotopes (N, O, H, B, C), and geostatistics to recognize nitrates sources and processes in shallow phreatic coastal aquifers: clues from the Metauro River Basin (Central Italy)

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Keywords: water pollution, stable isotopes, hydro-geochemistry.

The shallow phreatic coastal aquifer of the Metauro River valley has been suffering a persistent nitrate contamination issue since the 1970s, primarily driven by using agricultural fertilizers. Nitrate levels have reached alarming concentrations (over 300 mg/L), jeopardizing this vital water resource that sustains local drinking, agricultural, and industrial needs. As the aquifer faces mounting anthropogenic pressure, the quantity and quality of water are at risk, making the area a critical focus for social and scientific attention. Previous research has explored the chemical character of these waters. This research has unravelled the significant role of both natural and anthropogenic factors in altering their original composition especially in terms of elevated levels of nitrates and, to a lesser degree, chlorides, sodium, and sulphates.

In this study, we used a multi-isotopic approach to pinpoint the origin of nitrate contamination and the hydrogeochemical processes shaping the shallow phreatic aquifer. By analyzing δ^{15}N-NO_3, δ^{18}O-NO_3, δ^{11}B, and δ^{13}C-TDIC from 16 samples collected twice in April and October 2023, we identified useful insights to evaluate the shallow aquifer contamination. The δ^{13}C-TDIC ranges from -14.2 and -7.1‰ vs. V-PDB, with the higher values related to surface waters, thus suggesting interaction with the riverine carbonate-rich environment. Nitrate isotopes revealed distinct biogeochemical processes, with δ^{15}N-NO_3 values ranging from +2.3 and +23.2‰ and δ^{18}O-NO_3 between -3.9 and +20.2‰. While there were no drastic changes between the two surveys, most samples pointed to primary contamination by organic pollution sources (sewage and manure). Interestingly, samples with low nitrate concentrations (< 10 mg/L) showed heavier isotopic signatures, hinting at ongoing denitrification. By combining the δ^{15}N and δ^{11}B values, the latter ranging from +2.9 to +34.7‰, a more precise identification of the primary nitrate sources was constrained, mainly related to sewage and septic tank leaks. The geostatistical approach emphasized that high concentrations of nitrate were found throughout the whole extension of the river plain. However, near the Metauro River and the artificial channel crosscutting the study area, the NO_3 contents strongly decrease, pointing to significant interactions between surface water and groundwater.

S33.

Analytical geosciences towards cultural heritage valorization and conservation

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Mapping Rome's geo-cultural landscape: an interactive tool for geoscience education and heritage preservation

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Keywords: geotourism, cultural heritage, geosciences.

The city of Rome highlights throughout the world for its rich and various historical-cultural heritage, whose development and dissemination are strictly linked to the unique characteristics of its territory and the transformations it has undergone over time -both natural and human- induced. Understanding the environment, its natural risks and the resources it provides is essential not only for the health and well-being of the communities living there, but also for the conservation and enhancement of its cultural heritage. Rome serves as an exceptional natural and historical laboratory for communicating Geosciences thanks to its natural landscapes, which help reconstruct the geological evolution the region and its vast natural resources. The city's monumental heritage includes a wide array of lithological materials, such as marbles from the Mediterranean Basin. Fossil discoveries provide insights into past environments, while natural hazards —such as historical floods that repeatedly submerged the city's lower areas— highlight the city's vulnerability. Nevertheless, citizens' awareness of natural risks and resources remain limited. To address this, an interactive, user-friendly, georeferenced digital map of a portion of Rome has been created using the ArcGIS Pro platform. Designed to be used via smartphone in both outdoor and indoor environments, the map focuses on Rome's historic center and surrounding districts. The project identifies three key themes: Itineraries, Monuments, and Geosites. Currently, it features eight outdoor itineraries with an average of 8–9 stops each, two indoor monuments accessible via virtual tour, and twelve geosites. At each stop, users can access a detailed information sheet that combines scientific data in Geosciences with historical and cultural insights, including geological features, natural resources, risks, and historical context. This tool supports the dissemination of Earth Science knowledge and promotes geotourism in Rome, while also raising public awareness of the importance of preserving and valuing both natural and historical sites.

Safeguarding the Sacred Stone: 3D surveying of Rock-Hewn Heritage in Georgia (South Caucasus)

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Keywords: rock-cut heritage, remote sensing, 3D point clouds.

In the framework of a collaborative research project between the University of Siena – Centre of Geotechnologies, Italy, and the Ilia State University (Tbilisi, Georgia) an integrated geomatics fieldwork was carried out at seven major rock-cut heritage sites across Georgia. The oldest monastery, Uplistsikhe (Shida Kartli Region), is dated back to the 1st millennium BC; it was originally a pagan rock-hewn city, later transformed into a Christian centre (4th–10th century). The origin of the sites of Dodos Rqa (Kakheti Region), Natlismtsemeli (Kvemo Kartli Region) and Shiomgvime (Mtskheta-Mtianeti Region) is linked to a Mesopotamian group of Christian monks, namely "*13 Assyrian Fathers*", whose aim was the monastic life consolidation in Georgia (6th century). Vanis Kvabebi (Samtskhe-Javakheti Region) and Sabereebi (Kvemo Kartli Region) were created from the 8th to the 10th centuries, during the Medieval monastic expansion. The biggest monastery complex, Vardzia (Samtskhe-Javakheti Region), was constructed from the 12th to the 13th centuries (Golden Age of Georgia).

The primary objective of the study was to generate a comprehensive and scalable database of 3D point clouds aimed at supporting long-term monitoring and geotechnical-geomorphological analyses of these culturally and geologically important sites.

The survey approach combined Terrestrial Laser Scanning (TLS) acquisitions, using a Trimble™ TX8 scanner, and digital photogrammetry. For nadiral and oblique aerial imagery data acquisition, a DJI™ Mavic 2 Pro Unmanned Aerial System (UAS) was used.

The integration of TLS and UAS datasets was conducted through Structure-from-Motion (SfM) and point cloud registration workflows, allowing the production of high-resolution, georeferenced 3D models. The data processing and analysis was carried out using Agisoft Metashape™ and Trimble RealWorks™ software. In addition, the TLS point clouds were coloured by using a Nikon D7100 camera equipped with a fisheye lens.

These models serve as geospatial and architectural documentation, digital preservation, virtual access and as reference baseline for diachronic analysis and morphological monitoring aimed at highlighting cultural heritage resilience in the face of environmental and anthropogenic pressures.

Moreover, condition of mural paintings and surfaces as well as structural slope stability may be assessed and related remediation works established.

This multi-scale geospatial documentation effort lays the groundwork for long-term rock-cut heritage sites conservation strategies and supports their recognition within international frameworks such as the UNESCO World Heritage List. Only Vardzia has been listed since 2007 in the UNESCO Tentative List.

Diagnostic approaches for the conservation of Cefalù Cathedral's apse: a combination of non-invasive and traditional techniques

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Keywords: non-invasive, diagnostics, UNESCO site.

The Cathedral of Cefalù (Sicily, Italy) is masterpiece of Norman architecture and part of the UNESCO World Heritage Site "*Arab-Norman Palermo and the Cathedral Churches of Cefalù and Monreale*" since 2015. Among its most celebrated features is the apse mosaic, whose exceptional preservation is central to both its historical significance and current valorisation efforts.

In the framework of a recent restoration campaign, a diagnostic plan was developed to support the conservation of both structural and decorative elements in the apsidal area with two main aims: to assess the state of preservation and to characterise original materials, in order to devise and implement suitable intervention strategies.

Although studies focused on mortars and plasters for restoration purposes are common (Gulec & Ersen,1998; Carò & Di Giulio, 2004), no research has yet been conducted on the mosaic *tesserae*, masonry plasters, mortars, stuccoes, and coloured plasters of the Cathedral of Cefalù, making the present study a pioneering contribution to the field. To date, archaeometric analyses of the Cathedral's materials have been limited to the petrographic characterisation of the marly limestones found in the cloister, which have undergone considerable deterioration (Ercoli et al., 2004).

A combined methodological approach was adopted, integrating non-invasive techniques and traditional analytical methods. This strategy proved essential in ensuring a minimal impact on the artifacts while obtaining comprehensive data.

The study, indeed, involved the application of portable X-ray fluorescence (pXRF) for in situ analysis of glass mosaic *tesserae*, revealing evidence of glass recycling practices and identifying key chromophores responsible for the rich colour palette. Moreover, the results of chemical analysis demonstrated that the black tesserae were artificially produced, thereby ruling out the hypothesis of them being made from natural glass, i.e. obsidian. X-ray diffraction (XRD) on sampled plasters and mortars enabled the identification of carbonatic binders and degradation compounds such as calcium oxalates and sodium chloride, the latter likely attributable to the interaction between the masonry and marine aerosols, given the Cathedral's close proximity to the sea. Petrographic analysis of stuccoes and coloured plasters further revealed the composition of aggregates and binders and allowed for the identification of pigmentation techniques.

This study demonstrates how a thorough understanding of material properties—achieved through the integration of in situ non-invasive methods and ex situ laboratory analyses—represents a fundamental tool for the preservation of this invaluable heritage.

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How excavation activity is both a blessing and a curse for the paleontological heritage: the case study of the fossils from the "Lessinia Stone" in the Verona province (northern Italy)

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Keywords: Upper Cretaceous, quarries, geopaleontological heritage.

Among cultural heritage, fossils are one of the most "neglected" goods, especially in Italy, both for unawareness by the public and both for economic interests due to excavation activity. The Cretaceous sedimentary rocks of the Lessini Mountains, especially the "lastame" stone quarries of the surroundings of Sant'Anna d'Alfaedo (Verona province, Italy), hold some of the most important and largest marine vertebrate findings (e.g., sharks, mosasaurs, marine turtles) of northern Italy and many invertebrates. All these findings were possible thanks to the extensive quarrying activity present in those mountains for the extraction of the "lastame" (or "Lessinia Stone"), responsible for a high fraction of the local income of many activities. Unfortunately, partly due to National Cultural Heritage Laws, quarrymen are not incentivized to contact authorities or paleontologists when they find some valuable findings in fear of a halt of the excavation activity, harmful to their profit. It is not uncommon to see fossils destroyed or lost, hence hurting the paleontological heritage of the region and impeding scientific research, despite some steps forward are currently happening with some cooperations between paleontologists and quarrymen. We present the first risk management proposal for better securing the paleontological heritage of the "lastame" with analyses of vulnerability, magnitude of the various risks and possible solutions for securing these extremely valuable fossils from being lost forever.

Geomaterials from Venosa (PZ) catacombs: characterization and state of conservation

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Keywords: geomaterials, pigments, mineralogical analysis.

The aim of this study, developed in the framework of a PRIN 2022 (Venusia Judaica: Advanced tools for epigraphical, archaeological, geomineralogical investigation, sustainable fruition and preservation of the Jewish Catacombs of Venosa) granted to Università Orientale di Napoli and Università di Napoli FEDERICO II, is the mineralogical and petrographic characterization of the geomaterials (both natural and artificial) from the catacombs of Venosa (PZ). As mentioned above, it is part of a broader project aimed at creating an in-depth and innovative investigative tool for the Jewish catacombs of Venosa (PZ, Basilicata).

The catacombs appear as a series of corridors carved into the rock, along which the burials adorned with Jewish iconographies and epigraphs are located.

Thanks to minimally invasive sampling, different types of natural geomaterials (e.g. tuffs, conglomerate) and alteration products (e.g. efflorescence) were analyzed, highlighting the different lithologies present in the archaeological site and the different states and types of alteration.

Furthermore, using non-invasive in situ analyses, the pigments characterizing the main iconographies were analyzed, and a detailed study of the epigraphs at high magnifications was carried out.

Project proposal for the establishment of the Peloritani Mountains Mining Geopark: land development and eco-sustainable fruition of the geo-heritage of northeastern Sicily

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Keywords: geoheritage, mining geopark, Peloritani.

The creation of a mining geopark offers two opportunities: 1) to preserve the historical and geological heritage of the area, and 2) to enhance its economic value. This is because the exploitation of minerals and rocks creates a strong link between the territory and humans, affecting the cultural roots of the local population. Minerals in Sicily, both on the surface and underground, have been exploited by local communities since prehistoric times, including sulphur, halite, iron, silver and copper, among others. Such activities in the Peloritani Mountains have left interesting mining sites that are still sporadically explored by individuals and mineral collectors. These sites could easily be turned into geo-tourist attractions by including them in planned geo-routes, in collaboration with the local administrations of the villages of Antillo and Fiumedinisi, which are keen to re-evaluate their territories and improve their local economies. This project, called "GEO-ROUTES", is being developed by a team of academics with expertise in geology, petrography and geography, working at the University of Catania (duration 2 years). This proposal will allow the re-evaluation of old ore mines and provide a new economic impetus for the communities living in the Peloritani areas.

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Geoheritage valorisation and geosite mapping in the historical and environmental GeoMining Park of Sardinia

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Keywords: geodiversity, sustainable tourism, cultural landscape

Sardinia (Italy) is renowned for its exceptional geodiversity and mineral wealth, which have contributed to shaping both its natural environment and cultural identity. Its geo-mining heritage spans thousands of years, from the prehistoric use of obsidian to the large-scale industrial mining of the 19th and 20th centuries. This long and complex history of human interaction with the subsoil has left an indelible mark on the landscape, particularly in the southwestern area of the island, where mining districts such as Iglesias, Buggerru, and Montevecchio represent true open-air museums of geology, history, and industrial archaeology.

In this context, the Geological and Historical Environmental Park of Sardinia (recognized by UNESCO in 1997 as part of the Global Geoparks Network) plays a strategic role in safeguarding and promoting geoheritage through integrated conservation, education, and sustainable development. The present work aims to contribute to the valorization and inventory of geosites within this unique territory, by focusing on their scientific, educational, and touristic potential.

Through a multidisciplinary approach, combining geological field surveys, GIS-based mapping, and historical-archival research, the study identifies and describes key geosites that illustrate the geological evolution of Sardinia and its mining past. Particular attention is given to the correlation between lithologies, structural features, and ore deposits, as well as the anthropogenic transformation of the landscape.

Each geosite is assessed using qualitative criteria based on international methodologies (Reynard & Brilha, 2017), evaluating parameters such as scientific relevance, accessibility, state of conservation, and interpretive value. The resulting geoheritage framework provides a useful tool for local authorities and park managers in the planning of educational trails, geotourism routes, and conservation strategies, promoting awareness of Sardinia geological identity and fostering a sustainable connection between communities and their territory.

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Kras-Carso II Interreg European project. Research on geotouristic and scientific landmarks sponsoring the heritage of the future cross-border Kras-Carso Geopark

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Keywords: geopark, classical Karst Region, Rudist Limestone.

The Classical Karst cross-border area represents a "Gateway to the East," connecting the Mediterranean region to Europe. Thanks to opportunities provided by the EU Interreg Italy–Slovenia Programme 2021–2027, researchers from both countries are joining forces to support the sustainable valorisation of the geoheritage in the Classical Karst region. The main goal of the project is to promote sustainable development in the Karst area, including the establishment of a cross-border geopark. By highlighting exceptional geosites, the project aims to promote key geological and geomorphological features to the public. Activities include i) 3D modelling for the production of virtual outcrop models to make geosites more accessible, ii) dye-tracing experiments to improve our understanding of the hydrogeological dynamics in the karst, iii) drilling and studying a core across the Cretaceous-Paleogene boundary (K-Pg) to valorise the local record of the Chicxulub meteorite impact, the event that brought to the extinction of dinosaurs and iv) promotion of the area's palaeontological heritage, including dinosaur fossil fields. The scientific knowledge generated by these studies is transferred to the general public through the professional training of geopark guides, who then lead guided tours along routes that highlight and promote the geological heritage of the area. Outreach will also include an exhibition in Trieste showcasing the microscopic ecosystems of the Cretaceous–Eocene shallow-water carbonate platform of the Karst, now visible as marine fossil remains, such as foraminifera and algae, preserved within the rocks. The exhibition will also feature artistic images captured with a petrographic microscope under various polarized light settings, along with materials supporting the candidacy of Karst Rudist Limestone as a UNESCO Heritage Stone. Dedicated paths and cycling routes are being designed to guide visitors through such fascinating geological storytelling. Furthermore, workshops, outreach events and other initiatives are organized for the general public and stakeholders to raise awareness of the geodiversity richness. Collectively, the joint effort of the partners of this project converges toward the establishment of the Kras-Carso Geopark, an area that deserves preservation along with responsible and sustainable development.

Studies of hyblean chert raw materials provenance: the case study of Calicantone (Modica - RG)

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Keywords: chert, Hyblean foreland, Raman spectroscopy.

Rich in geomaterials, the South-Eastern Sicily was occupied since prehistoric times. In particular, the area of Hyblean foreland has been known as supply area for its abundance of chert outcrops in primary deposition as nodules and lists, essential raw material for the production of knapped lithic industries.Specifically, present in the Amerillo and Ragusa Formations (Leonardo Member), the hyblean chert has been exploited through a systematic strategy of the underground mining activity (e.g., Monte Tabuto and Contrada Coste mines), creating a real commercial network ("network della selce"- (Scerra, 2023).

This raw material has petrographic, micropaleontological and geochemical distinctive features, related to the depositional environment and the diagenetic evolution, essential in order to determine artifacts' origin. These identifying characters can be investigated through a non-invasive and multi-parametric protocol (NM-PCI) appliable for both geological and archaeological samples (Delluniversità et al., 2019).

The purpose of this contribution is to attempt a preliminarily reconstruction of the chert supply system used in the Early Bronze Age site of Calicantone (Modica -RG), located in the karst valley of Cava d'Ispica. Already known for its early and middle Bronze Age necropolis, the site has been investigated by the Archaeological Park of Cava Ispica and the University of Catania (2012-2015).

Excavations have returned a hut belonging to the Castelluccian culture, used from 1850 to 1650 BCE dating by *radiocarbon dating*, together with 50 artefacts of lithic industries (Sferrazza & Militello 2024) knapped using chert of different lithotypes and various tools (e.g. tranchet and blades).

To achieve this result, the chert industry was observed applying the NM-PCI protocol that includes macroscopical, mesoscopical (through a stereomicroscope) observations and non-destructive and portable instruments, as Raman spectroscopy, in order to characterize the mineralogical profile of specific phases present in the chert samples. In parallel, a colorimetric investigation was carried out and portable X-ray Fluorescence (pXRF) was used to define chemical characterization.

Results were compared with a chert lithotheque, composed by samples of Hyblean provenance characterised by this work group with the same protocol and subject to continuous implementation (Corrente et al., 2024). Such research is useful in order to track the prehistoric human presence and the ancient settlement strategies, based upon the exploitation and circulation of chert.

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Delluniversità E. et al. (2019) - Development of a multiparametric characterisation protocol for chert investigation and application on the Gargano Promontory mines. Archaeol. Anthropol. Sci. 11, 6037-6063, https:// doi.org/10.1007/s12520-019-00875-8.

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Non-Invasive analytical study of Early 20th-Century preparatory works: the case of Sartorio's Canvases for the Cathedral of Messina

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Keywords: not invasive analysis, painting techniques, modern pigments.

Between 1930 and 1932, Giulio Aristide Sartorio (1860–1932) produced a remarkable series of large canvas panels as full-scale preparatory studies for a planned mosaic decoration of the interior façade of the Cathedral of Messina, Italy. This church had been destroyed in the catastrophic 1908 earthquake. Although the mosaic project was ultimately never executed, Sartorio's 1:1 oil and pastel sketches remain a significant artistic achievement. Today, the 36 canvases are housed at the Seminario Arcivescovile "San Pio X" in Messina.

Recently, the Istituto Centrale per il Restauro conducted a technical and conservation study on the entire series. This adopted a fully non-invasive, multi-analytical methodology in order to identify the materials chosen by the artist, technical aspects and possible past restoration interventions. The diagnostic campaign was conducted in collaboration with the University of Catania, by using portable X-ray fluorescence (pXRF), portable Raman spectroscopy (pRS) and Diffuse Reflectance Infrared Fourier Transform spectroscopy (DRIFT).

This integrated approach made it possible to investigate several key aspects of the works. The most important are listed below:

- A wide variety of pigments were identified through the combined interpretation of pXRF and pRS data: inorganic pigments (e.g., chrome red, mars red, red lead, strontium yellow, chrome yellow, zinc yellow, a chromium-based green, and copper-arsenic greens like Scheele's or Paris green) and synthetic organic pigments (such as PO5 and azo compounds);
- Pigments were used in mixtures to obtain specific tones (e.g. Prussian blue appeared not only in blue tones but also in mixtures to achieve dark and green hues);
- Carbon-based black was likely used for black pastel details;
- White areas showed the presence of titanium white (anatase), lead white, and zinc white.
- The use of lithopone (zinc sulfide and barium sulfate), gypsum, and calcite was linked to ground layers or as fillers and extenders in the oil-based paint and pastel media.
- Metallic effects were also found: aluminum was detected in silver-toned areas, while copper and zinc were revealed in both gold and copper-colored sections.
- The binder is oil-based both in the paint and metallic pastes.
- Additionally, polyvinyl acetate (PVA) was detected by DRIFT in more recent repair work on the canvases.

Portable X-ray fluorescence analysis of natural and artificial glass tesserae of the 12th Century AD floor mosaic of Otranto Cathedral (Apulia, Southern Italy)

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Keywords: pXRF, obsidian, medieval mosaics.

The floor mosaic of the Cathedral of Otranto (Apulia, Southern Italy), which was created in the 12th century AD, exhibits a complex and elaborate iconographic program and encompasses the entirety of the floor surface of the nave, presbytery, transept, and apse of the sacred edifice. At the centre of the mosaic the Tree of Life (Gen 2,9; Pr 3,18; Rev 2,7; 22,14.19) stands as a principal image; radiating outward from it are diverse depictions that reference to Old Testament stories, the cyclical nature of time (as exemplified by the Cycle of Months), and scenes from medieval literature. The mosaic's tesserae measure about one centimetre on each side, and they were cut largely from polychrome limestones or marbles. However, in some areas of higher liturgical relevance and several scenes with high symbolic value, tesserae of natural black (obsidians) and coloured artificial glass are present. This contribution presents the analytical study carried out on natural (obsidian) and artificial glass tesserae, found in the apsidal and presbyterial area of the Otranto Cathedral, obtained by portable X-ray fluorescence spectroscopy (pXRF). The analyses enabled the differentiation between tesserae composed of natural glass and those made of artificial glass, owing to the distinct elemental compositions of the two glass types. The spectra acquired from the pXRF analyses of numerous obsidian tesserae of the Otranto Cathedral mosaic were compared with those acquired, with the same instrument and under the same operating conditions, from obsidian samples originating from the main sources in the Mediterranean area. The comparison of the chemical composition of Mediterranean obsidian geological outcrops with the spectra obtained from the analysis carried out on the obsidian's tesserae present in the Otranto mosaic allowed for the definition of their provenance. The study of the pXRF spectra relating to artificial glass tesserae of different colours allowed us to distinguish the main components used in the production of the glass and to obtain information regarding the provenance of the primary glass. The study of the constitutive nature of artificial glass and the identification of the source area of obsidian is critical because it provides information on the trade routes active in the Middle Ages, as well as cultural interactions between patron and artisan.

Inside the Painting: Science and Restoration of the wood panel painting "*Madonna con il Bambino, San Giovannino ed i Santi Zaccaria ed Elisabetta*" (Pinacoteca Metropolitana di Bari "Corrado Giaquinto" - Bari, Italy)

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Keywords: pXRF, obsidian, medieval mosaics.

The painted panel *'Madonna con il Bambino, San Giovannino ed i Santi Zaccaria ed Elisabetta'*, preserved at the Pinacoteca Metropolitana di Bari "Corrado Giaquinto", has undergone diagnostic analyses prior to the restoration intervention. The preliminary results allowed for the identification of the main types of binders and pigments used, the information regarding the stratigraphy of the painting, the techniques of execution, and the preparatory layer.

The scientific investigations started with non-invasive and non-destructive techniques, such as colorimetric analysis, technical photography (UV-IR), fibre optic reflectance spectroscopy (FORS), and X-ray fluorescence spectroscopy (XRF). The *in situ* studies, conducted directly on the painting inside the Pinacoteca laboratory, provided the initial results useful for identifying the most significant sampling areas of the work, to perform successive micro-invasive and micro-destructive analyses by matrix-assisted laser desorption/ionization mass spectrometry with time-of-flight analyser (MALDI-ToF-MS) and attenuated total reflectance Fourier transform infrared spectroscopy (FTIR-ATR). During the restoration phase, some micro-samples were taken from areas both not affected by interventions and integrated by recognisable previous restorations, as necessary to perform observations and stratigraphic analyses both by optical microscopy (OM) and advanced techniques such as scanning electron microscopy coupled with energy dispersive microanalysis (SEM-EDS). The multi-technique approach used for the diagnostic campaign reveals that the colour palette is consistent with those commonly used in the Renaissance period, as well as the animal glue of the preparatory layer and the triterpenic resin, obtained from the mastic shrub, which is used to protect and give brightness to the painting. The data obtained appear consistent with the period and provenance hypothesised by the historical-artistic study (early 16th century). The pictorial layer is analogous to that relating to the paintings of the schools suggested by art historians close to that of Raffaello Sanzio. The characteristics artistic style allows us to compare the paintings of the Bolognese Antonio Rimpatta and Antonio Pirri even if not by a technical point of view due to the lack of systematic diagnostic and archaeometric studies. These preliminary results, therefore, represent a working basis for future investigation. Anyway, the processing and comparison of analytical data have provided an important aid for the performance of the delicate restoration intervention.

A critical overview of risk functions for the analysis of the impact of indoor and outdoor microclimatic conditions on cultural heritage conservation

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Keywords: Microclimatology, cultural heritage, risk functions.

Microclimatic conditions – namely temperature, humidity (quantified through relative humidity or mixing ratio), natural and artificial illumination, air quality, etc. – have a direct or indirect impact on the conservation of cultural heritage both indoor (exhibition rooms, artefacts exposed in civil and religious buildings, display cases, archives and deposits, etc.) and outdoor (architectural works, sculptures, frescoes or murals, but also the geological and geomorphological heritage).

The risk analysis of potentially negative impacts of such conditions can be based on the product of three quantities (see, e.g., UNISDR, 2009): Risk = Hazard × Vulnerability × Damage. Here, Hazard is the probability that a given potentially hazardous event occur; Vulnerability (or Susceptibility) is the probability that the potentially hazardous event effectively produces damages; Damage (or Exposure) is the value of potentially damaged objects or the cost to restore the original conditions.

Starting from Lipfert (1989), several researchers proposed risk functions to quantify the effects of microclimatic conditions on artworks of different materials and taking into account different physical, chemical or biological processes (surface recession of carbonate rocks, corrosion of metals, paper degradation, wooden artworks, etc.; water condensation, dust deposition, salt weathering, freeze/thaw cycles, pests and mold infestation, etc.).

The goal of this presentation is to critically review some of the risk functions, which have been proposed in the scientific literature, with a specific focus on the following issues: a fully-rigorous probabilistic definition of hazard and vulnerability; the distinction of risk functions which refer either to hazard or to vulnerability; the difference among risk functions for long-lasting processes (e.g., long-lasting conditions which could favor microbiological infestation) and "instantaneous" phenomena (e.g., floods, landslides, earthquakes); the proper use of the probabilistic framework to differentiate risk analysis for processes related to physically-based thresholds (e.g., freezing/thawing cycles) or processes for which somehow subjective categorization is usually applied (e.g., growing-degree days, used to estimate life stages of insects).

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Research and preservation of Giuseppe De Nittis' paintings in "Pinacoteca De Nittis - Palazzo della Marra" with the use of portable equipment: a case of study

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Keywords: Impressionist paintings, pigments, on-site diagnostic.

In recent years, thanks to the work carried out by the Superintendency of Archaeology, Fine Arts and Landscape for the provinces of Barletta-Andria-Trani and Foggia, and the G. De Nittis Art Gallery (Barletta), it has been possible to conduct numerous research studies and conservation interventions on the pictorial works of the renowned artist Giuseppe De Nittis (Barletta 1846, Saint Germain en Laye 1884) donated by his wife, Léontine Lucile Gurvelle.The integrated use of portable X-ray fluorescence (pXRF), fibre optics reflectance spectroscopy (FORS), and technical ultraviolet and infrared (UV-IR) photography on the paintings *Procella* (or *Landscape with Clouds*, 1868) and *Natura morta* (or *Still Life with Clothes and Jewels*, 1882) allowed for the obtaining of technical data that significantly supports the research and preservation of De Nittis' paintings. These non-invasive analytical tools, when combined, facilitate a comprehensive understanding of the materials, techniques, and degradation phenomena inherent in such artworks, ultimately aiding auxiliary tailored conservation strategies. Diagnostic analyses in situ have made it possible to identify the composition of the preparatory layer and many of the numerous pigments used by the artist in his representation.These are similar to those used by the Impressionist Claude Monet, who was in contact with G. De Nittis. Coupling pXRF, FORS, and IR photography enables a multi-layered investigation that addresses both the visible and hidden aspects of the paintings. This strategy supports the accurate documentation of the materials and techniques, thereby guiding conservation interventions to maintain the artwork's integrity while respecting its historical authenticity. For Impressionist works, where bold brushstrokes and innovative colour applications are central to the artistic expression, an integrated analytical approach is vital. Moreover, no scientific research papers on G. De Nittis' paintings have been published, and this represents the first data on the colour palette of this great Italian artist. The research project at the museum on the study of De Nittis' painting techniques was also supported by diagnostic documents carried out by the Central Institute for Restoration (ICR) and by deeper examination of bibliography on De Nittis by the Superintendency of BAT and Foggia.

Argentiera di Sant'Anna (Stazzema, Alpi Apuane): an extraordinary example of Renaissance mining activity

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Keywords: renaissance mines, topographic survey, Pb-Zn(-Ag) ore.

Versilia (NW Tuscany) is a well-known tourist locality between the Ligurian Sea and the Alpi Apuane. Beach tourism is predominant, while, only in recent years, more and more excursionists are choosing alternative destinations aimed at hiking in the main sites of the Alpi Apuane UNESCO Geopark. However, many geosites remain unknown and struggle to enter cultural, scientific, and educational tourist itineraries. The mining sites are among the most prominent examples, and their history has always characterized life in this area. With the end of mining activities until the 80s, these sites fell into oblivion. Abandoned, they became, in some cases, the object of theft of artefacts and documentation.

This contribution is proposed as a further incentive to the historical, cultural, and scientific valorisation of the mining sites, considering one of the most historically relevant – the Argentiera di Sant'Anna mining complex (Stazzema). The purpose of this study is to explore and document the mining complex for its conservation and cultural enhancement, as well as for future geological surveys.

The ore consists of small lenses of galena (PbS) and sphalerite (ZnS) associated with Ag-rich tetrahedrite, hosted in tourmaline-bearing Filladi inferiori formation of Cambrian-Lower Ordovician age. Some authors have hypothesized that mining activities date back to the Etruscan/Roman period, but they remain hypotheses without any confirmation. The first documents date back to the 13th century under the control of the local nobles of Corvaia and Vallecchia. However, mining activities were minimal in an unfavourable political context. Only in the XVI century, with the annexation of Versilia to the Florentine Republic (Lodo of Pope Leone X, 1513), the Pb-Zn(-Ag) bodies were exploited for almost a century under the control of the Medici family. In the 19th and 20th centuries, only modest exploration activities were carried out. For this reason, the Renaissance mining complex is largely preserved, testified by the tunnels and voids with characteristic tool marks and "coffin" sections. The exploration and topographic survey of the Argentiera di Sant'Anna mining complex, along with the comparison with existing cartography, made it possible to delineate the underground heritage. The mining complex consists of 12 main underground mines and 12 minor excavations, totalling a spatial development of 3.5 km, of which approximately 34% are ancient tunnels entirely hand-dug. Almost all the underground mining heritage is accessible, except for two mines, which have their entrance blocked by landslide debris.

The Timpa delle Murge ophiolitic sequence (Southern Italy): a geological route in the Pollino UNESCO Global Geopark

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Keywords: geologic route, ophiolitic sequence, Pollino Massif.

The Pollino National Park, located on the border of Calabria and Basilicata in Italy, was included in the European Network of UNESCO Geoparks in 2015 due to its exceptional geodiversity. The Geosites have significant landscape and environmental value, making their geological characterization and accessibility particularly important. In this study, we focused on the geological route of Timpa delle Murge, near the Terranova del Pollino (PZ) village within the Pollino Massif. The Pollino Geotourism route, which spans between Basilicata and Calabria, provides an extraordinary immersion into the geodiversity of the southern Apennines, with particular emphasis on ophiolitic sequences. The Timpa delle Murge ophiolites do not exhibit any subduction-related high-pressure metamorphism (Bonardi et al., 1988). They consist of Mg-gabbro cumulates (Spadea, 1979) and are stratigraphically overlain by pillow lavas, pillow breccias, hyaloclastites, and diabases. The sedimentary cover comprises siliceous shales, radiolarian cherts, and limestones (Lanzafame et al., 1979). These rocks, remnants of ancient ocean floors, offer insights into the complex geological evolution behind the formation of the Apennine chain. Visitors can observe ophiolite outcrops, including serpentinite, gabbros, and basalts. These formations represent sections of the oceanic lithosphere that emerged due to the obduction process. Understanding and observing these geological formations allows for a deeper appreciation of tectonic plate dynamics and the interactions between different stratigraphic units. The synergy between landscape, geology, and biodiversity creates an immersive experience that merges the allure of nature tourism with the scientific significance of its rock formations. This Geotourism route, which is 720 meters long, begins in the village of Terranova del Pollino and highlights the existence of the ancient ocean basin, known as Tethys, at 1,300 meters and its subsequent closure. Along the route, visitors can observe ophiolitic rocks and a detailed panel that explains how following this geological itinerary takes you across the bottom of what was once an ocean. The scientific importance of Pollino National Park is a reference site for geodiversity and earth sciences. It is increasingly recognized as a significant destination for Geotourism, offering valuable opportunities to study and learn about geological heritage.

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Handheld Laser-Induced Breakdown Spectroscopy (hLIBS) for geochemical exploration: from prospect mining to extraterrestrial investigation

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Keywords: handheld LIBS, Geochemical fingerprinting, GeoLIBS.

Since the late 19th century, the origin of the Earth and the continuing evolution of its environment have been studied by geologists by analyzing minerals, rocks and soils. Laser-induced breakdown spectroscopy (LIBS) is a versatile geochemical technique able to capture in real-time the entire elemental composition of a sample, thus it is used in a wide range of applications, from Mars rovers to Earth rock identification. In particular, LIBS is capable of both qualitative and quantitative analysis of most elements in the periodic table depending on their intrinsic limit of detection in a specific material, and is particularly sensitive to the light elements H, Li, Be, B and C that are difficult to analyze by many other techniques. Thus, the broadband LIBS spectrum can be considered a diagnostic geochemical fingerprint (Harmon & Senesi, 2021; Senesi et al., 2021). More recently, the availability of reliable analytical instrumentation that can operate directly in field, such as handheld (h) LIBS, is in high demand. The role and performance of hLIBS devices in situ will be described in the context of different research applications while targeting specific questions of geological interest. The fast data acquisition and minimal sample preparation features of these instruments make them very attractive tools candidate for qualitative elemental analysis, microchemical mapping and sample selection. Furthermore, hLIBS is a very promising tool for use in planetary geochemical mapping, resource prospecting and hazard identification. There is a vast potential for the routine application of LIBS across a broad spectrum of the geosciences that is as yet only minimally realized.

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From deep subduction to Murano: the geoscience behind Venetian Crystal Glass

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Keywords: ancient mines, Western Alps, geotourism.

The valorization of cultural heritage often begins with understanding the natural materials from which it originates. The case of Venetian crystal glass, a Renaissance invention renowned for its purity and brilliance, is a striking example of how geoscientific investigation can illuminate the history and value of cultural artefacts. The key to the production of this transparent, colourless glass—developed in Murano in the 15th century—was the use of manganese oxide as a decolouriser, sourced exclusively from the manganese mine of Praborna (Saint-Marcel, Aosta Valley, Italy). Many geological studies in the last decades have revealed that the Praborna deposit is not only historically significant but also of extraordinary scientific interest. It represents a rare example of manganese-rich metasediments and metaophiolites that experienced subduction-related high-pressure metamorphism during the Alpine orogeny. Minerals such as braunite, piedmontite, spessartine, pyroxmangite, and the rare Mn-bearing omphacite known as "violane" crystallized under eclogite-facies conditions (~2.1 GPa, 550 °C), preserving an oxidation gradient reflective of fluid–rock interaction in subduction zones. Beyond its mineralogical variety—Praborna is the type locality for multiple rare species—the deposit demonstrates how the interplay between tectonics, metamorphism, and fluid mobility led to the natural formation of compounds later exploited for their optical and chromatic properties. In particular, the reaction Fe^{2+} (in molten glass) + Mn^{3+} → Fe^{3+} (colourless) + Mn^{2+} (pale pink) underpinned the glassmaking process. By manipulating this chemistry, Murano artisans achieved an effect visually akin to natural rock crystal, enabling the creation of mirrors, chalices, and luxury items exported across Europe. The integration of petrology, mineralogy, and archival history sheds light on a compelling geocultural narrative: from the Tethyan seafloor to subduction, from eclogite formation to glass furnaces. This multidisciplinary perspective not only enhances the scientific understanding of the Praborna system but also contributes to the protection, valorization, and communication of European material heritage, demonstrating how geosciences can inform both conservation and cultural storytelling.

Towards a new Heritage Stone: the Karst Rudist Limestone of Italy and Slovenia

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Keywords: Kras-Carso, Aurisina Stone, Heritage Stone.

The Classical Karst Region (Kras-Carso) is a cross-border area shared by Italy and Slovenia, from which the international scientific term "karst" is derived. The geodiversity of this region is linked to the evolution of the former Adriatic-Dinaric Carbonate Platform (Jurkovšek et al., 2016; Consorti et al., 2021; Bensi et al., 2022). On this platform, an Upper Cretaceous, rudist-rich shallow-water limestone was deposited, which entails the Italian "Aurisina Limestone" and the Slovenian Repen, Sežana and Lipica formations (Consorti et al., 2021; Bensi et al., 2022). These limestones are currently quarried on both sides of the border. In particular, the Aurisina Stone ("Pietra di Aurisina") has played a significant role in the cultural heritage of the Karst region, and several historical quarries are preserved in the area. Due to its geotechnical and ornamental qualities, the stone has been used since Roman times and throughout the centuries for construction purposes. Its use is also witnessed in important UNESCO World Heritage Sites, such as the Roman city of Aquileia and the Mausoleum of Theodoric in Ravenna. In the 19th century, the quarrying of this limestone underwent significant growth and development. From this period onwards, it has been traded at an international scale. This is evidenced, for instance, by the numerous monuments in Vienna and Budapest that make use of this stone (Previato, 2015). Within the framework of the Interreg project Kras-Carso II (2023-2026), a study of the Karst Rudist Limestone across Italy and Slovenia was undertaken to assess its suitability as IUGS Heritage Stone. For the preparation of the proposal: (1) the petrography of the different commercial varieties of rudist-bearing limestone quarried in the Karst has been described; (2) objective differences between commercial varieties of different ages and provenance have been identified; and (3) active and inactive quarries have been studied and mapped. Further data have been gathered concerning the historical use of the stone, which support the designation of Karst Rudist Limestone as a potential Heritage Stone, in accordance with IUGS standards. This contribution presents an overview of our dataset and results, which will form part of our proposal to the IUGS Subcommission on Heritage Stones.

Bensi S. et al. (2022) - The Classical Karst geopark. Geological Survey - Central Directorate for Environmental Protection, Energy and Sustainable Development of the Autonomous Region of Friuli Venezia Giulia, 164 pp., https://hdl.handle.net/11368/3053480.

Consorti L. et al. (2021) - The Mesozoic palaeoenvironmental richness of the Trieste Karst. 90. Congresso della Soc. Geol. It. - Trieste, 14-16 settembre 2021, Pre congress Field Trip N. 4. Periodico semestrale del Servizio Geologico d'Italia, ISPRA e della Società Geologica Italiana Geol. Field Trips & Maps, 13/2.2, 40 pp., https://doi.org/10.3301/GFT.2021.06.

Jurkovšek B. et al. (2016) - Geology of the classical karst region (SW Slovenia–NE Italy). J. Maps, 12(sup1), 352-362, https://doi.org/10.1080/17445647.2016.1215941.

Previato C. (2015) - Aquileia. Materiali, forme e sistemi costruttivi dall'età repubblicana imperiale, Padova University Press, 638 pp., https://hdl.handle.net/11577/3147546.

The role of vibrational spectroscopies in disclosing mineral specimens' manipulation

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Keywords: mineral forgeries, vibrational spectroscopies, imaging techniques.

Natural geological specimens, whose presence enriches museum collections around the world, are rightly regarded as fundamental elements of cultural heritage due to their inherent aesthetic qualities and their significance in the historical, symbolic, and technological development of human civilization.

Recently, this long-standing relationship has taken on an economic dimension, as the growing demand for such collectables has promoted forged minerals flowing into the market and, eventually, into museum collections (McClure & Smith, 2000). However, since the manipulation of natural specimens is solely intended to enhance their value as collectibles, inconsistencies are frequently introduced that may lead the public to misunderstand geological processes (Calik et al., 2019). As one of the primary roles of natural history museum is to increase audiences' awareness and understanding of natural processes (Artioli, 2022), the disclosure of geological forgeries plays a crucial role in the dissemination of knowledge.

In this context, it is important to recognize that a wide range of techniques have been employed to counterfeit Geoheritage specimens, including crystal remounting on geological matrices, dyeing, thermal and irradiation treatments, and polymer impregnation (Calik et al., 2019; McClure & Smith, 2000). While an extensive body of literature exists on the forgeries of cut and isolated gemstones, scientific research on the manipulation of uncut euhedral minerals embedded in geological matrices still remains limited.

As such, it is deemed necessary to characterize these specimens and the spurious materials involved in their alteration, employing analytical approaches analogous to those long accepted in the fields of art and archaeological conservation (Artioli, 2022). Moreover, the identification of these compounds proves critical for establishing the chronological framework of the intervention, as specific materials were predominantly employed during distinct time frames.

Accordingly, this study presents a series of case studies drawn from both modern and historical collections, encompassing examples of synthetic replicas, specimens remounted onto geological matrices, as well as those subjected to dyeing and polymer impregnation. The primary objective is to develop a robust analytical protocol capable of revealing various techniques of manipulation and identifying the associated non-authentic materials. To this end, a multi-analytical approach is employed, integrating macroscopic imaging with vibrational spectroscopic techniques. Digital photography, taken under ultraviolet lamp excitation, and hyperspectral imaging, evaluated in the short-wave infrared region, are utilized to detect the presence of spurious materials and their spatial distribution. Once identified, these areas undergo vibrational spectroscopic analysis—specifically Raman and Fourier-transform infrared (FTIR) spectroscopies—to chemically characterize the system and identify the incompatible or artificial materials (Bernardino et al., 2016).

Artioli G. (2022) - Authentication and the perception of fakes. forgeries of natural specimens. In: Salvadori M., Bernard E., Zamparo L., Baggio M. (Eds), Beyond forgery – Collecting, authentication and protection of cultural heritage, Antenor Quaderni 52, Padova University Press, Università degli Studi di Padova, 67-77, ISBN: 978-88-6938-292-5.

Bernardino N.D.E. et al. (2016) - Fake turquoises investigated by Raman microscopy. Forensic Sci. Int., 262, 196-200, https://doi.org/10.1016/j.forsciint.2016.03.041.

Calik A. et al. (2019) - Fake and Synthetic Minerals; A Way to Sustain the Gem Supply. In: Agnihotri A., Reddy K., Bansal A. (Eds), Environmental Geotechnology. Lecture Notes in Civil Engineering, 31, Springer, Singapore, 319-328, https://doi.org/10.1007/978-981-13-7010-6_30.

McClure SF. & Smith CP. (2000) - Gemstone Enhancement and Detection in the 1990s, Gems & Gemology, 36, 336-359, https://doi.org/10.5741/GEMS.36.4.336.

S34.

Global challenges: the future of museums and geoscience education

CONVENERS AND CHAIRPERSONS

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Rethinking the role of Natural History and Natural Science Museums as an educational vehicle in the field of geosciences

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Keywords: geosciences, Natural Museums, public education strategies.

In an era of growing environmental awareness, the outreach and education of Geosciences require a more multidisciplinary and engaging approach. Specifically, Art and Earth Sciences share a common heritage can be utilized to raise public awareness and promote sensitivity towards the importance of Geosciences. This work proposes the employment of artistic tools and methodologies to highlight the geological resources of the National territory and to rethink the role of museums as spaces for community participation and engagement. Specifically, our work explores how Italy's cultural heritage can serve as tool to valorize also the natural heritage and foster a greater public awareness working as a bridge between Geosciences and the general public with a redefinition of the role of the Natural History and Natural Science museums.

The growing sensitivity to biodiversity have led many contemporary artists to use their work to explore, preserve, and celebrate biodiversity. Through installations, videos, sculptures, and interventions, these artists aim to convey the message that biodiversity is not only a heritage to be conserved but also a form of natural wisdom from which to learn. In the words of biologist Edward O. Wilson, known as the so-called 'father of biodiversity', the diversity of life is an invaluable treasure and "To save biodiversity, we must make peace with nature". Contemporary art offers an answer to these concerns. Thanks to its capacity to communicate through emotions and sensorial experiences it indeed bypasses scientific language and speaks directly to the senses of the public. In this regard, artists such as Néle Azevedo, Ursula Biemann, Eduardo Srur, and Ernesto Neto use their projects as visual manifestos of this call to conservation, interpreting biodiversity as a theme that spans scientific, spiritual, and political spheres.

Rethinking the role of museums as spaces for interdisciplinary storytelling could allow a more active community engagement. At a National level, noteworthy examples of an already ongoing effort include the Civic Museum of Natural History in Milan and the Museum of Natural and Physical Sciences in Naples. Through workshops, exhibitions, and temporary displays, these institutions are committed to promoting scientific thinking and multiculturalism through various research themes, while also embracing new forms of engagement with the scientific heritage. Collaboration between scientists, artists, and communicators can generate innovative projects that stimulate curiosity and awareness towards natural landscapes and phenomena contributing to the creation of a more informed and engaged society.

In summary, our work aims to provide models of interdisciplinary collaboration with the aim of developing public education strategies and emphasizes the potential of an integrated approach in fostering a more inclusive and meaningful dialogue between science and society through the support of art and museums.

The Power of clay: geomaterials and resources in Museum Learning. Case study from the Exhibition "From Babylon to Baghdad: On Hammurabi's Path" at the University of Catania

Barone G.[1], Nicotra G.*[2], Mendola A.[3], Spironello M.Y.[2], Bertino A.[1-2], Corrente G.[2], Majorana S.[2], Borgesi A.[2], Fugazzotto M.[1] & Occhipinti R.[1]

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Keywords: sustainable materials, museum education, accessibility.

Museums act as dynamic cultural centres that encourage dialogue and curiosity through interactive and inclusive experiences. Ensuring scientific accessibility also means involving groups often excluded from traditional museum strategies, such as young people. In this spirit, the Museo delle Mirabilia e dei Saperi Siciliani (University of Catania) promotes cultural awareness through its university collections (Barone et al., 2023, 2024). An event worth mentioning was the international exhibition From Babylon to Baghdad - On Hammurabi's Path, with exhibits from the British Museum (London), the Pergamon Museum (Berlin) and the Royal Museums (Turin). Focusing on Mesopotamia in the second millennium BC, the exhibition conducted play-based workshops that simplified complex topics for children by highlighting geomaterials and integrating geological and archaeological data.

Linking geological data with archaeological evidence provides critical interpretative insights regarding raw materials, their treatment, and processing for the reconstruction of ancient production technologies and supply systems. Clay—ubiquitous in Mesopotamian material culture—is a fundamental geo-resource whose study enables reconstruction of the manufacturing process of ceramic production. Understanding its mineralogical composition, provenance, and transformation through firing allows archaeologists and geologists to contextualise artifacts within broader technological, economic, and environmental frameworks. These aspects were central to the workshops, which aimed to trace the sustainable use of natural resources and technological innovation across time (Flewitt et al., 2023: 139).

Hands-on activities encouraged participants to explore the connection between geology and archaeology through direct manipulation of clay and other geomaterials. Children recreated exhibition objects—such as Mesopotamian figurines and cylinder seals—using silicon molds and 3D-printed tools, simulating ancient techniques and experimenting with raw materials derived from geological processes. This tactile engagement encouraged critical comparisons with modern materials (e.g., plastic), fostering reflection on sustainability and resource use. A key geoscientific component was the use of digital tools simulating thin-section analysis under optical microscopy. Older students explored the mineralogical texture of ceramics, learning to identify inclusions and ceramic fabric.

These lab experiences emphasised the full interpretative pathway—from excavation to display—showing how geomaterial analysis is vital for reconstructing ancient technologies and enhancing heritage communication. Incorporating museum education strategies like child–adult, child–environment, and child–technology interaction (Andre et al., 2017), the initiative engaged children on sensory, emotional, and cognitive levels (Flewitt et al., 2023: 139). It demonstrated how interdisciplinary storytelling by archaeologists, geologists, and heritage scientists fosters geoscientific knowledge through cultural participation—contributing to greater accessibility, literacy, and inclusion.

Andre L. et al. (2017) - Museums as avenues of learning for children: a decade in Learning Environ Res, https://doi.org/10.1007/s10984-016-9222-9.

Barone G. et al. (2023) - Un approccio sperimentale multisensoriale per le Scienze della Terra. Museologia Scientifica, nuova serie, 17, 73-83.

Barone G. et al. (2024) - "Il Museo per tutti i Sensi": nuovo progetto inclusivo per il Museo delle Mirabilia dell'Università di Catania. Museologia Scientifica, nuova serie, 18, 114-127.

Flewitt R. (2023)- Young Children's Engagement with Objects in Science Museums: a Rapid Evidence Assessment of Research in The Museum Journal, 66(1), 129-148, https://doi.org/10.1111/cura.12540.

The role of Earth Sciences in the experimental laboratory "The SiMuA for young patients"

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Keywords: cultural welfare, edutainment, participatory methodology.

In recent years, the University Museum System (SiMuA) of the University of Catania has started a series of activities aimed at making its collections more accessible and inclusive, with particular attention to promoting STEM education and expanding audience engagement. Earth sciences, in particular, have been recognized as an effective tool to spark curiosity in children and engage young patients in the exploration of these subjects (Barone et al., 2023, 2024). Within this framework, the project "The SiMuA for Young Patients"—presented here—was developed to bring, for the first time, museum collections and activities beyond their traditional exhibition spaces, targeting a group usually excluded from cultural participation: children hospitalized in the Pediatric Clinic of "Rodolico-San Marco" University Hospital. The project combined educational and playful approaches with innovative goals related to health and well-being, through an integrated system based on multisensory and multidisciplinary experiences, with activities designed to cover various playful and educational areas.

For the occasion, a dedicated activity kit was created, including games, coloring materials, tactile elements, and digital tools, designed to actively engage young patients and offer them a multisensory experience that made cultural and scientific heritage tangible. A key role was assigned to storytelling focused on STEM subjects, particularly Earth Sciences, supported by the various tools included in the kit. Among these were two tactile books: the first dedicated to the little Elephant Liotru, featuring touchable samples such as sulfur powder; the second focused on the Lachea Island in Aci Trezza, offering a detailed geological overview, through raised illustrations and tactile materials. Other components included an origami workshop, where children recreated forms to explore mineralogy through the art of paper folding; a themed virtual tour; and a customized memory game showcasing items from the museum's collection.

The variety of approaches ensured a comprehensive experience - tactile, visual, manual and intellectual - transforming the hospital into a place where education, wellbeing, entertainment and inclusion converge. Thanks to a participatory process, effective and innovative interventions were developed, transforming the relationship between museum and hospital into a model of cultural welfare. The museum also becomes a facilitating agent in inclusion processes (Poce, 2019). The development of evaluation tools enabled the collection of encouraging data on the enjoyment and impact of the activities highlighting how the synergy between museology and medicine can open new perspectives for both the cultural and healthcare sectors.

Barone G. et al. (2023) - Un approccio sperimentale multisensoriale per le Scienze della Terra. Museologia Scientifica, nuova serie, 17, 73-83.

Barone G. et al. (2024) - "Il Museo per tutti i Sensi": nuovo progetto inclusivo per il Museo delle Mirabilia dell'Università di Catania. Museologia Scientifica, nuova serie, 18, 114-127.

Poce A. (2019) - Il valore sociale del museo agente di cambiamento. il progetto inclusive memory. In: Poce A. (a cura di), Studi avanzati di educazione museale. lezioni - advanced studies in museum education. Lectures, pp. 125-142.

Why and how to promote geology? Disaggregation of geological science in laboratorial activities: "hands-on" approach for stimulating curiosity, knowledge and awareness of the role of geology for the society

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Keywords: dissemination, geology awareness, practical laboratories.

Dissemination of geological concepts frequently focuses on specific, fascinating themes: fossils, minerals and volcanoes are the most typical topics that people associate to geology. This perception may reduce geology to a funny science that is poorly related to everyday life. This led to a scarce identification of geology as a useful science and to the perception of geologists as bizarre ("Indiana Jones" types) explorers, dressed in a funny way and equipped with an iconic hammer, that lose their time looking for fossils and shining minerals. An alternative view presents geologists as scientists focusing on the extraction of fossil fuels: this association led to a negative perception of geologists, as directly responsible for climate change and environmental degradation.

With these premises, it is easy to understand why the perception of geology as a useful science is strongly prevented: this is probably the main reason explaining the massive decrease of students in University Geology bachelor courses. Furthermore, in some countries such as Italy, teaching geology in secondary schools has strongly decreased in the last years. Another problem is also related to the way geology is presented to the students: geology is frequently taught with a notional approach, just remembering the names of minerals, rocks and fossils observed in pictures and never touched by hands. Also, in Italy, a large number of science teachers does not have a specific formation in Earth Sciences, being most of them biologists. The result is a decreased attractivity of this profession.

The founding of a dissemination project provided the opportunity to the Departments of Earth Sciences of Milano Statale and Roma La Sapienza Universities to test the efficiency of practical activities in diverse occasions (Science Festivals, Planet Earth Week, Mineral Shows, European Researchers Night, European Night of Museums, Training courses for teachers, activities with schools). Questionaries were addressed to the participants, and the elaboration of the answers produced. What emerges is a perception of the limited importance of geology before the activities, followed by an increased awareness of the importance of this discipline after. Results were achieved emphasizing the application of geological knowledge to land management, identification and exploitation of raw materials and understanding of the mechanisms of the climate changes. Promoting geology is complex, but results suggest that it is important to stress the role of geology to increase the awareness of this knowledge for the everyday life: the objects used (fossils and minerals, but also geological maps and thin sections of rocks) must be the means to promote geology, not the sole subjects of the dissemination activities. Dissemination should present geology as a multifaceted science, that deals with interesting objects whose role for the understanding of the processed ruling and shaping our planet is read by geologists.

Museum valorization of Barite, Fluorite, Pyrite, and Manganese Oxyhydroxides from Calabria: showcasing a Regional Mineral Heritage

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Keywords: minerals, museological valorization, geological-heritage.

Calabria region, located at the junction of major Mediterranean geodynamic domains, hosts a remarkable variety of mineral deposits shaped by the interplay of subduction, magmatism, metamorphism, and sedimentation. Among these, barite ($BaSO_4$), fluorite (CaF_2), pyrite (FeS_2) and manganese (Mn) oxides (Bloise et al., 2020) linked to hydrothermal systems, high-pressure metamorphism, and sedimentary-metamorphic processes, are minerals of high scientific, industrial, and geoheritage value. Their occurrences in northern Calabria, specifically in the Acquappesa, Cetraro, Mormanno and Serra D'Aiello areas, offer a unique opportunity to investigate mineral-forming processes in complex tectonic settings, while also fostering their museological and educational valorization. In this study, these minerals were investigated through an integrated multi-technique analytical approach, combining XRPD, FTIR, TG/DSC, SEM/EDS, TEM/EDS, EPMA, and ICP-MS. The combined use of these techniques provided insights into phase composition, crystal morphology, thermal behaviour, elemental distribution, and textural relationships with host rocks—contributing to the reconstruction of paragenetic sequences and genetic models. The studied crystals are generally well-formed and reach centimeter size. Beyond their scientific relevance, this study emphasizes the museological value of these minerals within the context of Calabria's geological heritage. As part of ongoing efforts to preserve and promote regional geodiversity, the specimens will be conserved and exhibited in the Mineralogy and Petrography section of the SiMU (Sistema Museale dell'Università della Calabria). In this context, special attention is given to the role of museums in transforming geological specimens into educational tools for understanding mineral-forming processes and the geological evolution of the southern Apennines. This work highlights the importance of mineral collections for research, education, and public engagement, while promoting the preservation of Calabria's geoheritage and sustainable development.

Bloise A. et al. (2020) - Mineralogical and geochemical characterization of asbestiform todorokite, birnessite, and ranciéite, and their host Mn-rich deposits from Serra D'Aiello (Southern Italy). Fibers, 8(2), 9.

Raman spectroscopy investigation of gemstones in ecclesiastical collections (Sicily, 18th-19th centuries)

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Keywords: ecclesiastical museums, devotional jewellery, Raman spectroscopy.

A non-invasive investigation campaign was conducted in three different ecclesiastical collections in the Eastern Sicily: Diocesan Museum at Caltagirone, Museum of Sacred Art of S. Nicolò at Militello in Val di Catania and Treasury of the church of Santa Maria Assunta at Randazzo. The aim was that of identifying the nature of the gemstones decorating various pieces of devotional jewellery (18th-19th centuries), among which a complex ex-voto parure sewn to the votive bodice vestment of the Immacolata statue at Caltagirone, various rings, a beaded necklace and another parure made of a necklace and earrings. The study was conducted exclusively by means of portable Raman spectroscopy, which proved efficient in recognizing the stones as rubies, garnets, spinels, diamonds and quartzes, together with some examples of glass, thus identifying different levels of richness in the various objects. The great part of the red gemstones analysed were garnets, therefore, the authors took advantage of this case study in museums to carry out a methodological focus on the Raman spectra of this mineral. In detail, two different methods were proposed for the spectral treatment, involving also a group of reference garnets of known composition. The first method consisted in the implementation of MIRAGEM+, a new version of the already known software MIRAGEM, that was tested to obtain the garnets' composition. The second was Principal Component Analysis (PCA), applied to all the spectra to check if it could discriminate groups of garnets on the basis of their composition. These two methods were then combined proving that both are reliable tools for the non-invasive characterization of garnets.

The "naturalia" section in the Wunderkammern: valorization, didactics and contemporary interpretations of scientific collecting

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Keywords: museology, naturalia, cognitive science.

Wunderkammern, or "chambers of wonders," represent an archetype of encyclopedic collecting, which flourished between the 16th and 18th centuries in northern Europe but also in Italy (Schlosser 1974; Lugli 1983). Within these collections, the naturalia section-minerals, fossils, shells, herbaria with plants with medicinal properties, rare or exotic animals-occupied a central role, testifying to a fascination with the unknown and a desire to understand and classify the natural world (Olmi, 1997).

In the contemporary context, the rediscovery and enhancement of these collections offers a valuable opportunity to reflect on the relationship between science, nature and society. Naturalia, if properly displayed and contextualized, can become highly effective tools for science popularization, environmental education and museum teaching. They also question us about the very meaning of collecting: an act that, today more than ever, can become responsible, critical and interdisciplinary (Pomian, 2007). Through cognitive science it is possible to analyze these spaces, not only as collections of curious objects or precursors of museums, but as mental and cultural devices that activate specific cognitive processes in the observer.

The talk proposes an analysis of the educational and cognitivist function of naturalia within historical Wunderkammern and modern museum exhibitions, with the aim of suggesting new modes of interpretation and design for an updated and accessible nature museology.

Lugli A. (1983) - Naturalia et Mirabilia. Il collezionismo enciclopedico nelle Wunderkammern d'Europa, Gabriele Mazzotta, 91-105 pp.

Olmi G. (1997) - L'arca di Noè. La natura in mostra e le sue meraviglie. In: Basso Peressut L. (Ed), Stanze della meraviglia. I musei della natura tra storia e progetto, Clueb 48-74 pp.

Pomian K. (2007) - Collezionisti, amatori e curiosi. Parigi-Venezia XVI-XVIII secolo, Il Saggiatore, 122-129 pp.

Schlosser J. Von (1974) - Raccolte d'arte e di meraviglie nel tardo Rinascimento, Sansoni, 101-106 pp.

A combined approach for digital curation and public outreach, the PALEOTWIN project: a central repository that integrates digital and physical objects

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Keywords: historical museum, digitization, virtual reality.

Communicating geosciences is a mandatory goal for universities and natural history museums worldwide, especially in a time of massive exploitation of natural resources and climate change. With the same pace, the number of digitized items has steadily increased in museum archives and 3D models are now increasingly requested for both scientific and dissemination purposes.

Thanks to PNRR Spoke 4: "Virtual Technologies for Museum and Art Collections", the Collezione di Geologia 'Museo Giovanni Capellini' in Bologna was chosen as a case study to set the ground to address multiple museums needs such as storing, curation and communication efforts related to the geo-paleontological heritage. Within this framework, the PALEOTWIN project aims to develop an integrated platform which includes a local server with dedicated software that manages a digital repository, imports catalogues data, configure temporary exhibitions and interreacts with different devices with a choice of layouts, for public engagement. Various industrial hardware prototypes are now being developed to be configured directly by museum staff through a "Drag & Drop" configurator and connected to the central repository. The first test for this application has been conceived for a temporary exhibition. The key components include four different settings: 1. The "Sancta Sanctorum", enabling a voice-guided museum experience via AI-powered avatars of the former museum directors sharing how the idea of scientific dissemination has changed over time. 2. The "Semantic Scenography", allowing interaction with prehistoric environments through interactive stations, integrated with physical objects on display. 3. The "Aptic Inclusive Table", facilitating dissemination toward visitors with disabilities allowing exploration through hearing and touch of 3D printed models. 4. The "Highlights XR", offering AR experiences activated via QR codes placed near ten museum display cases.

The project architecture is planned to be easily configurable, expandable and reliable, in order to address as many communications needs as possible. The software code will be released with CC0 license. The main aim of this project is thus to provide a broad audience of institutions with a low budget tool that enables museums and collections to manage and valorize their heritage.

The Quaternary calcareous tufa system of the "Parco Fluviale dell'Alta Valdelsa": a natural heritage and a training ground for geoscience outreach

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Keywords: calcareous tufa, Quaternary, geopark.

The "Parco Fluviale dell'Alta Valdelsa" is a small eco-geopark located along the Elsa River in the surroundings of Colle di Val d'Elsa (SI) in the middle of Tuscany. The main peculiarity of the park is the presence of a spectacular and delicate natural system of calcareous tufa barrages and pools, with waterfalls within a canyon valley, with historical-architectural inserts. This calcareous tufa system has been studied for a long time (see in Fazzuoli, 2019 with references therein) and has been well defined in Capezzuoli & Sandrelli (2004) and subsequent articles by the same authors. The calcareous tufa system dates to the Late Pleistocene-Holocene, and is currently being formed, and it has been the subject of revision as part of the recent CARG Project 286-Poggibonsi (Cornamusini et al., 2025).

The calcareous tufa system has been defined as fluvial terraced UBSU, which is the Upper Pleistocene Colle di Val d'Elsa synthem, subdivided through erosional surfaces in three subsynthems located at different altitudes, which are from the oldest, the L'Abbadia, Calcinaia and Torrente Foci subsynthems. More recent Holocene calcareous tufa deposits have been distinguished by Capezzuoli & Sandrelli (2004) as Bellavista and Poggibonsi synthems.

The calcareous tufa system of the Colle di Val d'Elsa synthem and the more recent similar deposits are part of the broader Quaternary carbonate system of the Valdelsa Basin, representing the last phases of deposition following the Pliocene marine transgression and the Pleistocene regression, which interested the entire hinterland of the Northern Apennines. In fact, Quaternary sedimentation was dominated by lacustrine and alluvial depositional systems that formed carbonate deposits of the Campiglia-Strove synthem. These, forming scattered carbonate plateaus overlying unconformably Pliocene marine deposits, have been subdivided into the older Strove subsynthem, Early? – Middle Pleistocene in age, and the Campiglia dei Foci subsynthem, Middle? – Late Pleistocene in age (the "Lago di Colle" paleolake). The latter subsynthem forms extensive carbonate plateaus consisting mainly of lacustrine limestone, outcropping in the surroundings of Colle di Val d'Elsa, where the Upper Pleistocene calcareous tufa system onlap it unconformably, as well evident within the geopark.

The park represents an open-air museum where naturalistic-environmental, historical-architectural and, above all, geological aspects can provide a training ground for education and scientific dissemination. In fact, in addition to the spectacular landscape aspects, it is interesting to observe the different sedimentological facies of the calcareous tufa and travertine related to the changes of depositional environments, to the paleoclimate conditions that strongly controlled the depositional and erosional phases, and to the Quaternary tectonics that controlled the distribution of carbonate systems and the fluvial geomorphological patterns.

Capezzuoli E. & Sandrelli F. (2004) - I sedimenti quaternari del settore meridionale della Valdelsa (Provincia di Siena). Il Quaternario - Italian Journal of Quaternary Sciences, 17(1), 33-40.

Cornamusini G. et al. (2025) - Note Illustrative della Carta Geologica d'Italia a scala 1:50.000, F. 286 Poggibonsi. ISPRA – Serv. Geol. d'It., Roma.

Fazzuoli M. (2019) - Mari, laghi, fiumi. Storia geologica di Colle di val d'Elsa e del suo territorio. Bollettino Società degli Amici dell'Arte di Colle di Val d'Elsa, 61-62, 6-59.

The mineralogical collection of Mining School "S. Mottura" in Caltanissetta: a starting point for a new mining era

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Keywords: minerals, collection, education.

Geopolitical reasons and economic interests are at the heart of the Critical Raw Materials Act that outlines the new European mining future. Europe returns to the mines to search for new raw materials, but above all, rare earths and minerals.

Since its foundation in 1862 the collection of Mining School "S.Mottura" in Caltanissetta has been the center for an intensive lab didactic based on Mining and on Earth Science.

After a reconstruction of history of minerals and rocks collections of the "Sebastiano Mottura" Mining School, collected along 160 years of school activity in main sicilian salt and sulphur mines, in this paper, it's exposed museum efforts to conserve and restore what remains of the ancient mines culture of central Sicily and how this data could be the new starting point for new research on critical minerals. The work outlines the case of magnesium and strontium.

From past to presence: enhancing Sicily's fossil heritage through VR and museum collections

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Keywords: geological collections, museum digitization, immersive education.

Scientific museums play a crucial role in promoting Earth Sciences, significantly contributing to public awareness on issues related to environmental protection and the conservation of natural heritage. The goal of this mission is the preservation and enhancement of collections, which represent the core of museum activities. In Sicily, the "G.G. Gemmellaro" Geological Museum of the University of Palermo houses an extensive fossil collection that documents the island's exceptional past biodiversity. Numerous fossiliferous deposits, particularly vertebrate sites, are now exhausted and known only through historical specimens, sometimes preserved in major Italian and European museums. The museum is actively engaged in the valorisation of these historical collections through digitization projects and scientific research. A recent project of "Servizio Civile Universale" enabled, with the involvement of eight volunteers, the digital cataloguing of over 2.000 specimens on the national platform SIGECweb, thereby offering participants valuable training in the museum sector. In parallel, research programs are being carried out on the collections using innovative methodologies and technologies, including taphonomic studies and absolute dating techniques, to investigate topics such as the origin and evolution of insular faunas and mesozoic paleogeography, thus enhancing the scientific value of the collections. The Gemmellaro Museum's collections have also had a tangible impact on the regional territory, with the establishment of local museums, often based on collections donated by private individuals, and encouraging municipal administrations to promote the safeguarding of geological heritage. A significant example is the Pliocene fossil site of Altavilla Milicia (PA), which is currently under consideration for geosite designation. To engage younger generations using innovative educational tools, the museum has created a multimedia space equipped with immersive VR headsets. These experiences represent an effective example of integration between scientific research and museum-based science communication. Visitors can explore three reconstructed prehistoric environments based on palaeobotanical and palaeontological data: the Cretaceous forests of Argentina inhabited by *Carnotaurus sastrei*, one of the most fearsome theropod predators; the Sicilian savannah from 200,000 years ago, populated by dwarf elephants; and a scene of daily life in Upper Palaeolithic Sicily, dating to approximately 14,500 years ago.

Geoscience for all: inclusive educational pathways and sensory-based learning at the Gemmellaro Museum

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Keywords: inclusion, educational activity, public engagement.

Since its reopening, the Gemmellaro Museum has focused its efforts on enhancing the dissemination of geoscientific and palaeontological knowledge through educational programs, guided tours, and workshops tailored to different educational levels. In recent years, attention has been increasingly focused on the development of inclusive projects aimed at improving accessibility for visitors with special needs. In this framework, two inclusive educational pathways have been implemented. The first is designed for children on the autism spectrum. The initiative seeks to enhance the museum experience through tactile engagement with geological and palaeontological samples, interactive digital media (e.g., tablet-based games and videos), and a specially prepared toolkit comprising visual aids and simplified educational materials to support teachers and facilitators during the visit. In a further effort to promote social inclusion, a collaborative agreement was established with the 'U.F.E. Palermo Association' (Utenti Familiari Esperti), a group whose members have direct or familial experience with psychiatric disorders. The resulting project, entitled *GeologicaMente*, encompassed curated visits to the Gemmellaro Museum and geo-educational field activities within the local territory. The project aimed to promote sensory-based learning through the direct observation and manipulation of geological and palaeontological samples, foster an understanding of cultural heritage conservation, management, and enhancement, and support the integration of classical literature with geoscientific narratives. This was achieved by linking local geological sites to myths, legends, and collective memory. Additionally, architectural heritage was reinterpreted through geological analysis by examining lithological materials employed in historical structures during field visits.

The Geo- & Bio-diversity Park

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Keywords: geodiversity, biodiversity, geosciences.

As part of the centenary celebrations of the University of Bari Aldo Moro, the event "Il Parco delle Geo & Biodiversità" (The Geo- & Bio-diversity Park) was held from October 4 to 7, 2024, in the wonderful setting of Parco 2 Giugno, an urban park in Bari, with the aim to strengthen institutional and scientific dialogue between "bio" and "geo" diversities and promote their dissemination. The event was jointly organized by the University of Bari and the Carabinieri Biodiversity Group and featured as a "village" of stands, each focused on a specific theme related to biodiversity and geodiversity.

The Carabinieri Biodiversity Group made visitors aware of the importance of protecting and safeguarding the environmental heritage, through educational laboratories and sensory experiences. Some of the main themes included forest biodiversity, wetlands and their protection, biocomplexity in the National Natural Reserves, wildlife conservation, the "A Tree for the Future" project and the activities of Territorial Centres for the Recovery of Confiscated/Seized Animals, the activities to discover the Sila area … even with virtual reality and nurseries, seeds and rare plants.

Several departments from University of Bari participated to the event, each offering educational content related to their respective fields. The Department of Earth and Geoenvironmental Sciences sensibilized the visitors to geodiversity in fossils, minerals, rocks, and in the landscape, emphasizing its role in supporting biodiversity, regulating natural processes (such as erosion and water cycles), and providing resources and raw materials for human societies. Particular attention was paid to the geodiversity of the MURGEOPARK UNESCO Global Geopark. Research activities in geosciences were illustrated through demonstrations and interactive laboratories, also using research cutting-edge instruments as educational tools. The Department of Veterinary Medicine featured a stand showcasing the recovery and conservation of wildlife, focusing on species conservation and ecosystem balance. The exhibition also addressed conservation of livestock species in Puglia and initiatives such as DNA extraction for bio-banks and the production of wool in the region. Wild boar management projects in nature reserves, such as the Alta Murgia National Park, were also highlighted. The Department of Biosciences, Biotechnology, and Environment focused on the biodiversity of aquatic and terrestrial ecosystems in Apulia. The stand displayed images, videos, and preparations of various species and habitats, with biologists on hand to explain modern research techniques. Finally, the Department of Soil, Plant, and Food Sciences illustrated the biodiversity of Apulian agroforestry ecosystems, showcasing protection activities for arthropod fauna and using digital technologies for monitoring. The event was also sponsored by the Municipality of Bari and attracted about 7,000 visitors of all ages and educational backgrounds.

Can a collection of Roman stones bring communities closer to Geosciences? The Francesco Belli Collection at the Earth Sciences Museum of the University of Bari

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Keywords: stone collection, marble, outreach.

The Francesco Belli Collection, preserved at the Earth Sciences Museum of the University of Bari, offers a unique opportunity to explore how historical geological heritage can be reinterpreted as a tool for public engagement and geoscience communication. Originally assembled in the 19th century by Francesco Belli and his son Filippo, the collection comprises 577 samples of ancient Roman decorative marbles and stones, widely used throughout history in architecture and art. The collection is included in the *Catalogo generale dei Beni Culturali* and each tile is marked by a ICCD number.

Samples are meticulously labeled and catalogued, reflecting antiquarian knowledge of the time and offering insight into the cultural and material significance of stone in the Roman world. Recently, the collection was the focus of a multidisciplinary project aimed at revalorizing it through updated scientific classification, digital documentation, and public outreach initiatives.

Specific efforts have included petrographic reassessment of the lithologies, correction of provenance data, and the development of a searchable digital database, enriched with high-resolution images and descriptive metadata. A dedicated website provides public access to a selection of samples and notes that connect geological features to historical contexts. These actions transform the Belli Collection from a static historical archive into a dynamic interface for learning and cultural dialogue.

Included in the Museum guided tours, exhibitions, and educational programs targeting schools and university students, the collection now serves as a platform to foster geoscientific literacy and awareness of geoheritage. It also supports archaeometric research by offering a valuable reference set for the provenance study of ancient stone materials in archaeological and artistic contexts.

By illustrating the historical extraction, trade, reuse, and symbolism of natural stone, the Belli Collection connects ancient practices to contemporary issues such as sustainability, resource management, and environmental awareness. It demonstrates how geosciences are not only about physical processes, but are deeply intertwined with human history and identity. As such, the project promotes a more inclusive and interdisciplinary understanding of Earth sciences, positioning University Museums as key actors in public education and engagement.

Collecting Power. Mineralogy, Heritage, and Historical Narratives in Italy

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Keywords: geo-mineralogical collections, Collegio Nazareno, cabinet.

Geo-mineralogical museum collections embody multifaceted historical, scientific, and cultural significance. Beyond their contribution to the development of Earth sciences, they reflect structures of power, regional representation, and systems of knowledge. As collected objects, rocks and minerals functioned as instruments of authority and identity, shaping heritage narratives and reinforcing sociopolitical agendas across various historical contexts (e.g., Vogel, 2015).

This work adopts a case-study approach to examine how, in 18th- and 19th-century Italy, geo-mineralogical collections housed in natural history cabinets functioned as critical loci of scientific production, sociocultural influence, and the consolidation of epistemic and institutional legitimacy. These dynamics are elucidated through an analysis of the recent initiatives undertaken to recover, study, and valorize the geo-mineralogical collections originally assembled in the Mineralogical Cabinet of the Collegio Nazareno (Crocetti et al., 1997), presently preserved at the San Giuseppe Calasanzio Institute in Rome. To date, 1714 geo-mineralogical specimens have been identified and examined in relation to original archival sources, such as notebooks and inventories, kept at the Archive of the Collegio Nazareno, enabling a contextualized reconstruction of the collection's historical and scientific significance.

The comparative analysis of historical records and recovered specimens has made it possible to trace previously undocumented material evidence of collecting practices carried out by key figures in the history of Italian Earth sciences—namely Giovanni Vincenzo Petrini (1725–1814), Scipione Breislak (1748–1826), and Carlo Giuseppe Gismondi (1762–1824). These naturalists significantly contributed to the formation and enrichment of the mineralogical cabinet's collections, acquiring specimens that also played an integral role in their own scientific investigations. Moreover, this study has led to the rediscovery of the overlooked figure of Augusto Zanotelli (b. 1860), the 19th-century curator of the Mineralogical Cabinet.

Finally, the comprehensive investigation of the recovered specimens alongside archival materials has illuminated broader dynamics of knowledge production, cultural legitimization, and governance that underpinned the collecting practices of the Mineralogical Cabinet. These dynamics are exemplified by the provenance of specimens donated by emperors (Mottana et al., 2012; Franza & Pratesi, 2023), high prelates (e.g., Cardinal Stefano Borgia), members of royalty (e.g., Charles Theodore of Wittelsbach), and prominent naturalists (e.g., Déodat de Dolomieu), thus underscoring the entanglement of scientific collecting with political, religious, and cultural institutions.

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Franza A. & Pratesi G. (2023) - Dono Imperiale. La collezione mineralogica dell'Imperatore Giuseppe II al Collegio Nazareno di Roma. Firenze University Press, 98 pp., https://doi.org/10.36253/979-12-215-0235-0.

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Vogel J. (2015) - Stony realms: mineral collections as markers of social, cultural and political spaces in the 18th and early 19th Century. Hist. Soc. Res., 40(1), 301-320, https://doi.org/10.12759/hsr.40.2015.1.301 -3.

The role of mining, archaeo-mining, archaeo-industrial, territorial museums: the example of the "Museo Sulphur" of Perticara (RN)

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Keywords: Museo Sulphur, Perticara, sulfur mine.

Museums and mineralogical collections play a key role in the conservation of great value cultural heritages. In addition, museums and collections offer a strong contribution to the scientific research and scientific outreach contributing to the citizens science. Among the huge Italian cultural heritage, there are some geological, mineralogical, paleontological, archaeo-mining museums displaying a strong bond with the local territory. This powerful territorial identity implementing their historical, cultural, social, educational value and passing on to future generations information and traditions that would be difficult to preserve.

This is the case of the "Museo Sulphur" of Perticara, located in Novafeltria (RN, Italy). The museum was opened in the 70s, shortly after the closure of the mining activity (1964), becoming one of the first significant examples of industrial archaeology in Italy.

Nowadays, the museum is hosted in the ex-"Certino" sulphur mineyard and offers a unique opportunity to discover the unknown world of the sulphur. The exhibition is developed into different paths showing a detailed mineralogical and geological collection and the main instruments adopted in the mining process. This archeo-mine treasure preserves an important historical archive and today acts as a centre to disseminate the mining and historical culture of the Perticara mine.

Recently, the museum has taken part in several scientific projects playing a central role in connecting the territory with several universities and research teams, speleological and exploration groups. The museum contributed to the re-exploration of the ancient galleries in the area by the Regional Speleological Federation of Emilia-Romagna (FSRER). The evidences of the explorations are reported in numerous studies published in the volume *"Gessi e solfi della Romagna orientale"* (Garberi et al., 2016). Moreover, the museum has also been decisive in recent scientific collaborations (e.g. Giordani et al., 2022, 2024, 2025), adding great scientific value to the museum and the territory.

"Sulphur" is a clear example of how collaboration between scientific research and museums can be fundamental, on the one hand, to scientific knowledge. On the other hand, in protecting and disseminating a precious cultural heritage. This collaboration, also contributes and implements awareness in the citizens by ensuring the historical memory. In this specific case, great credit goes to the passionate volunteers of the *Pro Loco* di Perticara, who have been managing the museum for decades, taking care of collections, materials, providing information and spaces to young students and to the entire community.

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Giordani M. et al. (2024) - High-levels of toxic elements and radioactivity in an abandoned sulphur mine: Insights on the origin and associated environmental concerns. Science of the Total Environment, *906*, p.167498, https://doi.org/10.1016/j.scitotenv.2023.167498.

Giordani M. et al. (2022) - Could soluble minerals be hazardous to human health? Evidence from fibrous epsomite. *Environmental Research*, *206*, p.112579, https://doi.org/10.1016/j.envres.2021.112579.

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A physical and virtual paleontological exhibition to enhance the legacy of the youthful studies at Gravina in Puglia (southern Italy) of Arcangelo Scacchi (1810–1893)

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Keywords: Arcangelo Scacchi, paleontological exhibitions, dissemination.

Arcangelo Scacchi (1810-1893), one of the greatest geologists of the 19th century, known worldwide for his contributions to the fields of mineralogy and volcanology, began his career with works on malacology and zoology. In this regard, in 1835 he published 'Notizie intorno alle conchiglie e agli zoofiti fossili delle vicinanze di Gravina in Puglia' (News about fossil shells and zoophytes from the vicinity of Gravina in Puglia), in which he reported on numerous fossils, mostly molluscs, collected in a small area located a few kilometres south of Gravina in Puglia (southern Italy). The work includes the identification and description of about 170 species of mollusc (including 13 new ones) coming from Lower Pleistocene deposits. Scacchi original collection, which included valuable type material, was preserved at the Museum of Palaeontology of the University of Naples 'Federico II'. Unfortunately, part of the material was lost or destroyed and only 9 taxa described by Scacchi are still present. Based on recently resampled fossils, a temporary exhibitions was set up in 2021 (Lippolis et al., 2024). A page on a well-known 3D model portal (Sketchfab) hosts some 3D models of these specimens made with the photogrammetry technique. The 3D models can be viewed with smartphones or PCs, with VR viewers or printed with special 3D printers, facilitating accessibility for people with disabilities. This exhibition could become a tool for the preservation of palaeontological remains of international importance and an opportunity for the public to learn about this type of geo-cultural heritage, enriching the potential experiences of (geo) dissemination in the territory.

Lippolis E. et al. (2024) - From Geohistory to the Future: A Tribute to the Youthful Palaeontological Studies at Gravina in Puglia of Arcangelo Scacchi (1810–1893), the First Modern Geoscientist in the MurGEopark (aUGGp, Southern Italy). Geosciences, 14(12), 343, https://doi.org/10.3390/geosciences14120343.

The strategy of a science outreach center near Europe's highest active volcano

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Keywords: Etna, INGV, outreach.

The Istituto Nazionale di Geofisica e Vulcanologia (INGV) over its 25 years of activity as an excellent institution in research, monitoring and surveillance within the geosciences field, has also acquired significant experience in science communication and outreach releated to geosciences.

The Osservatorio Etneo of the INGV is now embrancing a new challenge in this sector by promoting the establishment of an outreach center on the slopes of Mount Etna, the largest active volcano in Europe. The experience gained through various educational and dissemination activities has highlighted the importance of strengthening and enhancing the relationship between researchers and the population, and in particular with students of all educational levels.

Knowledge of one's local area from both cultural and geoscientific perspectives, including awareness of potential natural hazards, is essential to raise awareness and educate society to greater respect for the territory, to adopt adequate prevention measures to mitigate the effects caused by natural disasters and a more conscious and sustainable use of local resources.

For this purpose, the Centro Museale e Divulgativo of INGV-OE was established in Nicolosi, a town on the southern slope of Etna and home to the Parco dell'Etna. The outreach center is conceived as a space where visitors can "observe, understand, and learn" and it is designed to be a distinctive and innovative element and create opportunities for interaction and dialogue with the researchers of the Osservatorio Etneo.

Visitors will have access to exhibition spaces where they can observe scientific instruments, volcanic rocks from Mount Etna, scale models of the volcano's morphology, and real-time data and information on the volcano's current activity. The learning experience will be enriched by seminar and information activities, specific to each target audience, and laboratory and experiential activities.

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Visitors will have access to exhibition spaces where they can observe scientific instruments, volcanic rocks from Mount Etna, scale models of the volcano's morphology, and real-time data and information on the volcano's current activity. The learning experience will be enriched by seminar and information activities, specific to each target audience, and laboratory and experiential activities.

The use of arsenic and mercury compounds in bird taxidermy in the 18th and 19th century: insight from the Natural History Museum of Florence by non destructive nuclear techniques

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Keywords: natural history museums, taxidermy, non-invasive analysis.

The preservation of taxidermized animals has been instrumental in the development of modern science, serving as essential references for taxonomy, comparative anatomy, and biodiversity studies. To ensure long-term conservation, explorers, collectors, and scientists had to develop effective preservation methods against pests. The earliest surviving examples of bird skins are dated to the 18th century, as earlier ones were likely lost due to inadequate treatments (Barbagli & Violani, 2010). Bird taxidermy advanced significantly in the 19th century. One widely used preservative was 'arsenical soap', created by Jean-Baptiste Bécœur (1718–1777), though its formula was published only in 1801 (Henon & Mouton-Fontenille, 1801).

Rare examples of 18th-century bird specimens are preserved at La Specola Museum, part of the Natural History Museum of the University of Florence, which houses one of Italy's most important ornithological collections. However scarce information is available on the preservation methods used at the time. It is possible that Florentine conservators accessed Bécœur's recipe before its official publication through scientific exchanges. Another hypothesis is the use of corrosive sublimate (mercury dichloride), known to have been employed in La Specola's ceroplastic lab for preserving anatomical parts to copy in wax models.

To investigate the preservation techniques and materials used, a selection of 18th- and 19th-century taxidermized parrots from La Specola was analysed non-invasively and non-destructively at INFN LABEC laboratory (Florence). Using Ion Beam Analysis techniques, namely PIXE, PIGE and RBS, with a 3 MV Tandetron accelerator (Chiari, 2023), the elemental composition from points on the breast and beak of each parrot was determined. X-ray radiography further revealed their internal structures and mounting techniques, exploiting a newly developed tomograph in the framework of the PNRR PE5 project CHANGES.

A clear distinction between 18th-century and 19th-century specimens emerged. All specimens contain arsenic (As) and mercury (Hg), but 18th-century birds were richer in Hg, while 19th-century ones contained more As. Probably corrosive sublimate was used in earlier specimens and arsenical soap in later ones. It remains to clarify whether both substances were used simultaneously or successively. The presence of As in oldest specimens should be related to later dry treatment of the feathers. Radiographs showed that 18th-century birds had simpler internal structures with metal wires without any signs of later reworking. The 19th-century examples displayed more advanced mannequin-like supports.

These findings not only enhance understanding of early taxidermy practices but also inform proper conservation and handling strategies. The study highlights the scientific value of natural history collections and the benefits of interdisciplinary research at the intersection of zoology, physics, history of science, and earth sciences.

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Chiari M. (2023) - External Beam IBA Measurements for Cultural Heritage. Appl. Sci., 13, 3366, https://doi.org/10.3390/app13053366.

Henon J. M. & Mouton-Fontenille M. J. P. (1801) - Observations et expériences sur l'art d'empailler et de conserver les oiseaux. Bruyset ainé, Lyon, 99 pp.

A new life for the Collezione di Mineralogia of the Museo Diffuso delle Scienze (MuDeS - Parma University): innovative pathways to engage society in geoscience awareness

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Keywords: geoscience communication, inclusive museology, thematic pathways.

Despite geosciences play a crucial role in addressing today's global challenges, public perception of their societal relevance remains limited. Natural History Museum collections can act as bridges between science and society, fostering inclusive, interdisciplinary, and participatory education.

The *Collezione di Mineralogia* of the *Museo Diffuso delle Scienze* (Parma University) is currently undergoing a major reorganization. The project focuses on reinterpreting the Museum's historical collections through a contemporary lens by developing some thematic pathways that connect mineralogy with urgent societal issues. The main relevant interpretative path are:

strategic resources in a changing world. By displaying selected mineral specimens alongside interactive maps and infographics, the exhibition invites visitors to explore the global supply chains of rare minerals, the socio-political contexts of mining, and the environmental costs associated with extraction. It stimulates critical thinking about resource dependency, circular economy, and responsible consumption.

seeing the invisible. This digital pathway introduces visitors to the complex geometries of crystal structures through immersive technologies and 3D visualization tools; visitors can interact with mineral models at the atomic scale using rotation, zooming, and dissecting them virtually to better understand materials in 3D space, support conceptual understanding of crystallography, and make scientific contents concrete and for visitors of all ages.

the sound of stones. An interdisciplinary itinerary which highlights how minerals are used for their acoustic, aesthetic, and functional properties in the crafting of musical instruments: clay in ocarinas, quartz in lithophones, metals in bells, or mica in varnishes for string instruments. The section includes audio samples and interactive stations where visitors can hear and feel the sounds of minerals, merging scientific content with sensory engagement and cultural history.

Minerals and Disability. An inclusive pathway which explores both the physical accessibility of the museum and the technological applications of minerals in assistive devices. Visitors learn how materials such as silicon, titanium, and rare earth elements are essential for hearing aids, prosthetics, wheelchairs, and augmentative communication tools. The display integrates tactile models, Braille panels, audio descriptions, and visual supports, creating a learning environment accessible to people with diverse abilities and cognitive profiles, and promoting a broader dialogue on the social dimensions of materials science.

By linking mineralogy to contemporary themes such as sustainability, inclusion, and equality, the project encourages a broader and more diverse audience to appreciate the societal value of Earth sciences. The Museum becomes not only a place of preservation but also a space for dialogue, reflection, and active participation in shaping a sustainable future.

Giuliana the Whale: integrating geoscience, cinema and museum practice for public outreach and scientific dissemination

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Keywords: stratigraphy, fossil whale, cinematic storytelling.

In 2000, during field activities near the San Giuliano artificial lake (Matera, Southern Italy), was uncovered partial skeletal remains of a massive Early Pleistocene cetacean, likely the largest baleen whale ever recorded in the Mediterranean (Bianucci et al., 2019). This exceptional fossil—later nicknamed *Giuliana*—became a cornerstone for new scientific, museological, and communicative strategies aimed at reinterpreting and sharing the geological history of the region.

Twenty years later, within the framework of the Geoarchaeo Project (PON "Research & Innovation" 2014–2020, ARS01_01249), a multidisciplinary investigation was launched in collaboration with the Museo Nazionale di Matera. Geological mapping and sedimentological, micropaleontological, paleoecological, and palynological were carried out to reconstruct the depositional context of the fossil analyses (Meo et al., 2024; Amore et al., 2025).

Stratigraphic units composed mainly of silts and silty clays with bioclastic silty-sands in the upper succession indicated a low-energy marine environment, interpreted using sequence stratigraphy (Catuneanu & Zecchin, 2020).

Beyond the scientific findings, this case study underscores the museum's role as a dynamic platform for public engagement. A central outcome of the project was the production of a 10-minute cinematic documentary, blending scientific content with the narrative and visual grammar of film. Developed through collaboration between researchers, filmmakers, and production companies, this video storytelling initiative represents an innovative tool for public outreach, especially in the context of digital transition and audience diversification (https://www.youtube.com/watch?v=eU-0D80X6GQ).

The cinematic format was not merely illustrative, but structurally integrated into the museum's communication strategy. By adopting a modern illustrative style and emotionally engaging narrative, the video clearly translate complex scientific research into an accessible and appealing experience. This approach has proven particularly effective in engaging younger audiences and fostering broader cultural participation around geoscientific themes.

The documentary is now part of the permanent exhibition dedicated to *Giuliana the Whale* at the National Museum of Matera, where the restored fossil is displayed. This project exemplifies how the integration of geosciences, museology, and cinematic media can bridge the gap between scientific research and the wider public. It also offers a replicable model for the sustainable and creative enhancement of geological heritage, aligning with current global challenges in museum practice, including climate awareness, digital innovation, and interdisciplinary education.

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The mineralogical collections of the Earth Sciences Department, University of Milano: history, heritage, and research perspectives

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Keywords: mineral collection.

The Mineralogical section of the Museum of Earth Sciences of the University of Milano holds a remarkable and historically significant mineralogical heritage. Officially established in 2004, its roots date back to the foundation of the Institute of Mineralogy in 1931. The museum's foundation was laid by Professor Emanuele Grill through the acquisition of the prestigious collection of Eugenio Bazzi. Over the decades, the mineral collections expanded through important contributions from Magistretti, Sigismund, Piccinelli, Traverso, and others, now comprising over 4,000 mineral specimens.

Among the highlights are exquisite examples of twinned orthoclase from Baveno, demantoids from Val Malenco, amethysts from Traversella, and rare minerals such as bazzite. These specimens have long served scientific research and university teaching, contributing to pioneering studies in feldspar crystallography and in the chemistry of rare earth elements in pegmatitic environments (Fagnani, 1950; Andreoli, 1936). The museum also houses an important collection of ornamental stones and historical petrographic samples.

Recent efforts have focused on cataloging, preservation, and valorization, including the development of high-resolution 3D models for selected specimens. These digital tools—particularly useful in education—complement but do not replace the physical experience of the collections, which remain central to their scientific, didactic, and cultural mission.

The collections today represent a valuable resource for the scientific community and a bridge between the historical foundations and future developments of mineralogical research especially in the Milano University.

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The "Quattro Evangelisti" pegmatitic blocks of the Museo La Specola: a restoration and re-exhibition project

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Keywords: Pegmatite, Foresite, restoration.

Elba Island occupies a prominent place in the history of world mineralogy also for the extraordinary richness and complexity of its granitic pegmatites (Pratesi & Bonazzi, 2012). One of the most famous and iconic finds are the "Four Evangelists", four large portions of pegmatitic geodes rich in crystallizations. They come from the site of Masso di Fonte del Prete, southeast of San Piero in Campo, later called Masso Foresi, in honor of Raffaello Foresi (1820-1876), who directed the extraction campaigns of 1872, as reported by Roster (Roster, 1876; Pezzotta, 2021). These blocks are enormous fragments of large miarolitic cavities, lined with crystals, formed inside the pegmatitic bodies during the last phases of their cooling. The paragenesis is typical of pegmatites with the presence of tourmaline (Elbaite), pink beryl, quartz, orthoclase, pollucite, petalite, lepidolite and zeolites (heulandite, chabasite, natrolite, stilbite and crookeite). Characteristic is the presence, on the elbaitic tourmalines, of a zeolitic encrustation initially described, in 1874, as a new mineralogical species and named "foresite", subsequently identified as a mixture of stilbite and crookeite (Pratesi & Bonazzi, 2012). The unique and evocative name of these specimens was given in 1876 when, during a visit to the Foresi Museum in Portoferraio, a monk, overwhelmed by wonder, kneeling before them, proclaimed them to be the Four Evangelists. Following the death of Raffaello Foresi in 1876, his heirs decided to sell the entire collection, including the Four Evangelists, which was purchased in the same year by the University of Florence (Moggi Cecchi et al., 2021). The collection was integrated with the litho-mineralogical collections of the Natural History Museum of the University of Florence, now part of the University Museum System, where they are currently preserved. However, their "colossal" dimensions pose significant challenges for a museum display, requiring large spaces, adequate structural supports and lighting designed to fully valorize them. Taking advantage of the transfer of the litho-mineralogical collection to the "La Specola" Museum, the Museum System planned their display in the new exhibition center in Via La Pira, annexed to the University Museum of Geology and Paleontology. In this context, it was deemed appropriate to carry out a thorough cleaning and consolidation of the finds, carried out at the specialized laboratories of the MCP company in Pioltello. The specimens were initially dry cleaned with a low-pressure sandblaster with calcium carbonate powder, then accurately vacuumed and the existing fractures were consolidated. The intervention highlighted the presence of previously barely visible mineralogical phases and evidenced the presence of two complementary parts, probably two parts of the same geode, appropriately placed next to each other in the display.

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Restoration and preservation of meteorites from the Museum of Nature and Humankind (MNU)

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Keywords: meteorites, conservation, museum.

Meteorites are rock fragments from asteroids and/or planetesimals. Together with samples returned from exploratory space missions, meteorites represent a very important resource for deepening our geological knowledge of the Solar System's bodies. The historical meteorite collections in museums, therefore, represent a very important resource for scholars of planetary geology as well as a decisive driver to fascinate and attract visitors to geological and mineralogical subjects. The strategic importance of these materials, however, raises serious questions about their preservation and how they are displayed to the public to preclude chemical or physical degradation of the samples (Welzenbach et al., 2006). Meteorites, in fact, naturally tend to degrade due to terrestrial weathering since their arrival on Earth. Thus, the preservation of the samples could be problematic. To limit these phenomena, the conditions of conservation and display should be optimised by minimising the sample's exposure to the Earth's atmosphere. This type of conservation, using argon gas or nitrogen, is often challenging to implement or economically unsustainable for many museums. It is therefore necessary to find alternative methods that ensure the preservation of the meteoritic samples under environmental conditions, often resulting in 'cracks' and visible surface alteration, such as Fe-Ni metal oxidation in metal-rich samples. This work aimed to develop a conservative, scientifically accurate approach to limit these alteration phenomena. The proposed protocol is easily reversible and does not contaminate the sample, making it suitable for future studies. Given the high variety of meteorites at the 'Alessandro Guastoni' mineralogy section of the Museum of Nature and Humankind (MNU), and the need to preserve the most valuable samples for the annual geological training for astronauts as part of the European Space Agency's (ESA)-PANGAEA project, we tested and optimised an economical and expeditious method of restoring and preserving meteorites under ambient conditions. The methodology begins with a preliminary characterization of the altered regions of the sample using X-ray diffraction, allowing for the identification of mineralogical changes resulting from alteration processes. The sample is then subjected to a restoration treatment involving nitric acid (HNO_3) dissolved in ethanol. After chemical treatment, the specimen is thoroughly dried and subsequently placed under high vacuum conditions to promote outgassing and ensure the complete removal of moisture from the surface. Finally, a thin protective coating of Paraloid B-44 acrylic resin is applied to the specimen. This type of coating, already tested for the preservation of ancient metals (Ćurković et al., 2012), provides practical preservation under ambient conditions, specifically when relative humidity is maintained below 45%, thereby ensuring the stability of the sample over the medium to long term. This acrylic resin, already used in various fields to preserve ancient metals, showed promising results even on meteoritic samples. It is very effective for the case study due to its high solubility in acetone, which allows it to be removed without employing invasive and potentially destructive mechanical treatments.

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The Vesuvian Collection of the Real Mineralogical Museum, University of Naples Federico II (Italy): a newly designated space for its exhibition, research and public engagement

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Keywords: Mineralogy, Vesuvio, Napoli.

In the heart of the city of Naples (Italy), in a superb sixteenth-century building, the Bourbons established the *Real Museo Mineralogico*, in April 1801, to promote the study of mineralogy in the Kingdom of Naples. Now the *Real Museo Mineralogico* of the University of Naples Federico II (RMMN) preserves more than 50.000 objects, mainly consisting of minerals and rocks of global provenance but also teaching mineral models, mineralogical instruments and a remarkable library.

The RMMN housed one of the world's finest collections of minerals from Somma-Vesuvius volcanic complex (Naples), a specialized regional and historical collection, containing many significant mineral specimens. It offers also a glimpse into the products of Somma-Vesuvius volcano activity not only with minerals and rocks but also with lava, ejecta, fumarolic samples, pyroclastics and is still being actively studied and added to by research scientists. The Vesuvian Collection is housed in the so-called "Scacchi room", a large and bright room dedicated to Arcangelo Scacchi, director of the Museum from 1844 to 1892. The collection includes specimens of varying size and quality for use as exhibition, teaching and research aims. On display is a fine selection of minerals organized in classes by chemistry according to the systematics of the Dana classification.

As part of the recent renovation and adaptation works for the removal of physical, cognitive and sensorial barriers in the museum (Grant PNRR M1C3 – Investimento 1.2 – Istituti pubblici non afferenti al MiC e private, 2.120.000,00 €), a new space has been added to the Scacchi room, allowing not only to expand the exhibition of Vesuvian minerals with the addition of other showcases but also to exhibit samples stored for years in the museum deposits.

Included in the exhibit of the newly renovated room are volcanic products referring to different eruptions. Our idea was to tell the eruptive history of Somma Vesuvio volcanic complex through its geological products. Lavas, rocks, minerals, pyroclasts tell the changes that the territory has undergone over the centuries and the impact that the volcano has had on the culture of the Neapolitan people. It is an interdisciplinary itinerary, planned to talk about science, volcanology and mineralogy, but also history of territory, history of science and collecting, literature and art. The main specimens now on display are: 1) the pumice from 4.000 ka BP (Early Bronze Age) referring to the Avellino pumice eruption, a catastrophic event which devastated a large part of the Campanian plane and the numerous prehistoric human settlements; 2) minerals and pumices from the famous 79 AD eruptive event, that destroyed the towns of Pompeii, Herculaneum, Oplontis and Stabiae; 3) lavas and minerals from the violent eruption started on December 1631, after more than five centuries of quiescence; 4) minerals related to Vesuvius eruptions occurred in the nineteenth century; 5) minerals and ash samples that covered the city of Naples during the 1906 eruption, as well as samples from 1929 until lavas and bombs expelled from Vesuvius crater during the last eruptive event in 1944.

Moreover, objects of everyday life are also on view in the new showcases, such as two bunches of grapes, a bell and a little anchor, part of an old arquebus with its flint found under the lava of 1794 Vesuvius eruption (Torre del Greco town).

The Historical 'Stella Polare' Collection at the Museo Regionale di Scienze Naturali di Torino: an historical, scientific, and ostensive rediscovery

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Keywords: Duca degli Abruzzi, Franz Josef Land archipelago, historic rock collection.

The "Stella Polare" collection includes rock samples gathered during the expedition organized by H.R.H. Luigi Amedeo di Savoia, Duca degli Abruzzi, in an attempt to reach the North Pole during the winter of 1899–1900. The "Stella Polare" Expedition—named after the ship used—was an exploratory mission through the Franz Joseph Land archipelago, located just above the 80th parallel. It belongs to the tradition of noble-led expeditions that characterized the 19th century.

The collection is currently preserved at the Museo Regionale di Scienze Naturali di Torino and is part of the mineralogical-lithological series belonging to the University of Turin. It consists mainly of effusive magmatic rocks such as tholeiitic basalts, basaltic andesites, and sub-intrusive rocks like dolerites. Also present are sedimentary rocks (sandstones, siltstones, jasper), high-grade metamorphic rocks (granulites), and a notable number of mineral specimens (quartz, opal, chalcedony, calcite, and zeolites).

The rediscovery and study of these petrographic samples from such remote areas has enhanced the value of the collection from historical, scientific, and exhibition perspectives. In particular, on the occasion of the reopening of the Museo Regionale di Scienze Naturali di Torino (MRSN) on January 12, 2024, a new exhibition space titled "Ark of Explorations" was inaugurated. It is dedicated to the major voyages and explorations that have enriched the museum collections.

The exhibition is designed to resemble the hold of a ship, with boxes and historical containers from which animals, minerals, rocks, and other naturalistic objects emerge. The twenty-two wooden ribs of the ship structure form an itinerary exploring the themes of travel, featuring route maps, documents, films, photographs, and objects of historical and scientific interest. Two of these ribs are dedicated to the Duca degli Abruzzi's Arctic expedition and display naturalistic materials, including a selection of petrographic samples from the prestigious "Stella Polare" collection.

The "Dinosaurs" exhibition: a museum key for children education, teacher training, outreach and marketing

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Keywords: museum, education, outreach.

Media simplification and the entertainment market often deal with "dinosaurs," encompassing in this simple and somehow familiar name a very complex biological and ecological reality, spread in different habitats over a large part of the planet and in a time span that is hard to imagine when compared with that of human evolution. In such a long time, evolutionary mechanisms and natural selection have worked, as evidenced whenever paleontological remains have been discovered and studied. This is a fascinating scientific topic to explore, which the Museum of Natural History of the University of Pisa decided to present to its audience through educational, didactic and outreach experiences with innovative and participatory methodologies and, ideally, using digital technologies as well. The first step of the project is the temporary exhibition "Dinosaurs", curated by the company Naturaliter s.r.l., which will remain in the Museum for one year. This exhibition, located in spatial and narrative continuity with the permanent display of the Museum on dinosaurs and birds evolution, consists of twenty life size models of dinosaurs and other Mesozoic reptiles, some of them animated (animatronics), accompanied by tactile copies of fossil skeleton elements and explanatory panels.

Starting with topics of great scientific interest, but also of great fascination, such as the most famous of the great reptiles of the past, the causes of their extinction, and the ecological consequences of their disappearance, the project aims to promote awareness of present mass extinction and ecological and climate changes on planet Earth, pressing issue which cannot be any longer ignored and that should be part of every European citizen's cultural background.

The exhibition is accompanied by several outreach events: a lecture series by established scientists (available on the youtube channel of the Museum), thematic tours aimed at young people aged 18-29 and led by well-known youtubers, and activities for families. On this occasion, the museum's educational paths dealing with palaeontology have been renewed to fully integrate the temporary exhibit and new educational materials have been developed, with a special focus on primary school. Moreover, training courses for teachers of all levels are proposed. The educational originality of the project consists in conveying, through the history and the great diversity achieved by dinosaurs, evolutionary, ecological and morpho-functional contents that can also be applied to broader contexts (such as that of today's vertebrates and the current ecological context, without neglecting the complex issues related to the controversial role played by the human species). Finally, an original Museum line of gadgets for the bookshop was created by a young artist with scientific advice from Museum experts.

Will QR codes be able to engage high-school students?

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Keywords: graphic project, videos, high-school students engagement.

To promote Earth Sciences, we have undertaken a graphic project, aiming to introduce high school graduates to a possible university career in Geological Sciences.

In particular, the project consists in the production of posters for public billboards that were put up in several South-West Tuscany cities, with preferential location near high schools or other areas of intense student transit.

The posters do not contain images or explanatory text. They report just 20 QR codes that link to 20 different videos, each lasting a maximum of 1 minute. The videos are grouped according to 7 actions (i.e., "Save your Planet", "Know your Planet", "Explore your Planet", "Observe your Planet", "Measure your Planet", "Study your Planet" and "A Job for your Planet") and can be visualized at the YouTube page of the Siena Geology section https://www.youtube.com/@geologiasiena4713/shorts. Well before the public billboards posting (which took place in the first week of May), the videos received numerous views (for example, total of 8074 views on April 22) and have been shared on our Facebook and Instagram pages.

The videos have been enthusiastically realized by undergraduate and PhD students, who explained what a Geological Sciences lesson consists of, underlining the variety and the present-day importance of the topics covered in our university career. Most of the videos were directly recorded during research or didactic activities in different labs and on the field, following the 7 actions reported above. As a further positive consequence, the initiative had the advantage of merging together students from different academic years and PhD students, thus contributing to ongoing orienting activities and strengthening the effectiveness of knowledge transfer between different student classes.

S35.

Roots and future of Geosciences: a historical perspective

Conveners and Chairpersons

Simone Fabbi (Sapienza Università di Roma)

Anna Giamborino (Università di Bologna)

Daniele Musumeci (Università di Catania)

Ezio Vaccari (Università dell'Insubria)

Some liked it hot in 1852: a study about the thermal springs of Stigliano (Tolfa Mts., Latium)

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Keywords: Stigliano Springs, Tolfa Mts., history of hydrogeology.

In the history of geological studies of the Rome area, Giuseppe Ponzi (1805-1885) represents a leading figure during 19th century. Around 1840, he started surveys of the surroundings of the town, continuing the work in the following decades with his disciples, thus establishing a modern school of geology and paleontology at the Pontifical University. Among the young followers of Ponzi, there was an eclectic personage, Tommaso Tittoni (1855-1931), jurist, diplomat and politician and amateur geologist; friend of Quintino Sella, he has been among the founders of the Italian Geological Society in 1881, serving as its first Treasurer for about 20 years (Argentieri et al. 2024). Early in his career, before being absorbed by public engagements, Tittoni devoted himself to geological research. From 1879 to 1884, he performed, under the supervision of Ponzi and helped by Romolo Meli (1852-1920), the 1:25.000 scale geological mapping of a wide area of Latium, between the Sabatini volcanic district, the Tolfa Mts. and the Thyrrenian coast. The map was published with a companion memoir (Tittoni, 1885) and proved useful for the subsequent preparation, by the engineers of the Royal Geological Survey, of two sheets of the Geological map of the Kingdom of Italy, edited in 1888. However, this story has a prequel, dating back to the middle of the century and related to Tittoni's ancestry.

Tittoni belonged to a wealthy family of merchants and countryside tenants from Manziana, a village close to the Bracciano lake, about 50 km NW of Rome. His father Vincenzo and his brother Angelo participated, as well as Ponzi, to the defense of the Roman Republic in 1849. The knowledge of the territory was a priority for the Tittoni family, insofar as useful for the estate administration.

This contribution focuses on a study on sulphur thermal waters of Stigliano, near Canale Monterano, in the eastern sector of the Tolfa Mounts. Author of the work were Tommaso's uncle, Angelo Tittoni, and Decio Zenitter (Zenitter & Tittoni, 1852). The Stigliano thermal springs, utilized at least since the 3rd century b.C., has been identified as the *Aquae Apollinares veteres*, after the interpretation of the springs of Vicarello, on the Bracciano lake northern shore, as the *Aquae Apollinares novae*. Relying on the results of the study, Zenitter and Tittoni expanded their business; in fact, the landowner Prince Clemente Altieri, disinterested in his estate, gave Stigliano in emphyteusis to the two hustling entrepreneurs, who thus reopened the thermal baths. The particularity of the 1852 article lies in its precocity, because modern studies on geology, hydrography and hydrogeology of southern Etruria started only years later, in the wake of the national geological mapping process (Capelli et al., 2018).

Argentieri A. et al. (2024) - Tommaso Tittoni, a geologist to the Prime Ministership. Abstract Book "Geology for a sustainable management of our planet", Società Geologica Italiana, 357, https://doi.org/10.3301/ABSGL2024.02.

Capelli G. et al. (2018) - Acque sotterranee nell'Etruria meridionale laziale. Una ricerca che perdura da millenni. Acque Sotterranee - Italian Journal of Groundwater, AS27-370, 75-80, https://doi.org/10.7343/as-2018-370.

Tittoni T. (1885) - La regione trachitica dell'Agro Sabatino e Cerite. Bollettino della Società Geologica Italiana, 4, fasc. 1, pp. 337 – 376, con allegata Carta geologica alla scala 1:50.000.

Zenitter D. & Tittoni A. (1852) - Osservazioni sulle acque termali sulfuree di Stigliano. Tip. Puccinelli, 1852.

Tito Alippi, the scientist of the ethereal

Argentieri A.*[1-5], Alippi A.[2], Alippi C.[3], De Ritis R.[4-5] & Rotella G.[1-5]

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Keywords: Tito Alippi, brontìdi, history of seismology.

Between the end of 19th and the first decade of 20th century, several Italian scientists devoted themselves to the study of acoustic phenomena in nature (Argentieri et al., 2024). This contribution focuses on Tito Alippi (1870-1959), physicist and meteorologist, who, at that time, was the leading figure on this specific field of research. At the outbreak of WW1, alas, investigations on roars was abruptly quitted, overwhelmed by the sound of guns.

The birth of seismology in Italy dates back to early 19th century, after the reconstitution of the Society of Jesus at the behest of Pope Pius VII. Jesuits established in fact scientific observatories in Europe and on other continents, in order to acquire quantitative data on natural phenomena and ensure population health and safety. Besides astronomy, the religious scientists promoted meteorological, geodetical seismological and geomagnetic measurements. It was not until 1868 that the first seismograph was installed in Europe: on the initiative of father Angelo Secchi, the Toscolano Observatory of Frascati, on the Alban Hills near Rome, hosted a seismoscope made by another Jesuit, Giovanni Egidi (Udìas, 2009). Shortly after the unification of Italy, the new Kingdom of Italy had to face two strong earthquakes: Casamicciola (1883) and Diano Marina (1887). Thus, the process of structuration of the national seismic survey began, culminating in the establishment of the *Istituto Nazionale di Geofisica* in 1936 (Foresta Martin & Calcara, 2010).

Besides major earthquakes, mysterious acoustic phenomena, diffusely felt throughout the country, stimulated the interest of the scientific community. The inadequacy of the technological level in that period, unluckily, hindered quantitative advancements about the origin of roars; the assumptions made referred the phenomena, depending on the case, to seismic activity, atmospheric dynamics, sea movements, groundwater circulation or other sources. Moreover, the uncertainties on the genesis determined a wide variety of terminology, feeding the halo of mystery that still resists now around roars (Argentieri et al., 2024). The work of the pioneer seismologists of early 20th century produced therefore merely descriptive contributions on localization and chronology of the registered events, with attempts at classification. Among all, Tito Alippi deserves credit for his efforts to understand roars, and mostly for the proposal of adoption of the univocal term "brontìdi" (Alippi, 1911), derived from ancient greek and meaning "similar to thunder".

The scientific production of Alippi ranges about various topics: seismology, experimental physics, meteorology, scientific dissemination and even parapsychology and metapsychical experiments. The common thread was the interest for intangible and invisible phenomena. For this reason, we pay a tribute to an unconventional scholar: Tito Alippi, the scientist of the ethereal.

Alippi T. (1911) - Nuovo contributo all'inchiesta sui "brontídi". Bollettino della Società Sismologica italiana, 15, 65-77.

Argentieri A. et al. (2024) - Tanto rumore per qualcosa: i misteriosi brontídi - Much ado about something: the misterious "brontídi". Acque Sotterranee - Italian Journal of Groundwater, - AS51-844, 67-71, https://doi.org/10.7343/as-2024-844.

Foresta Martin F. & Calcara G. (2010) - Per una storia della geofisica italiana. La nascita dell'Istituto Nazionale di Geofisica (1936) e la figura di Antonino Lo Surdo. Springer, Milano.

Udìas A. (2009) - Jesuits studies of earthquakes and seismological stations. In Kölbl-Ebert M. (ed.) "Geology and Religion: A History of Harmony and Hostility", The Geological Society of London Special Publication, 310, 135-143.

Geoheritage in the rupestrian town of Laterza (Puglia, southern Italy): the example of the Mascheroni Fountain

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Keywords: geoheritage, fountain, rupestrian town.

Starting from the historical attractiveness of the ancient "Fontana dei Mascheroni" (Great Masks Fountain) of the rupestrian town of Laterza (Puglia, southern Italy), the connection between geological features of the area and the ancestral origin of the city could be proposed to a large audience, representing an intriguing opportunity to develop themes useful for geotouristic purposes. This topic is of paramount importance since the town of Laterza is located at the boundary between the MurGEopark, the most recent UGCp (UNESCO Global Geopark) of Italy, and the geo-fascinating "Terra delle Gravine" Regional Park, making it the ideal starting point for both parks.

The nuclear issue: the contribution of the Earth Sciences in a historical perspective

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Keywords: history of geosciences, history of nuclear energy.

In the last few years, the historiography on nuclear energy has been thriving in an impressive way owing to a renewed interest that is also fueled by some of today's urgent issues. Several scholars have suggested that nuclear studies have been experiencing a renaissance, which has been positively enlivened by innovative theoretical and methodological approaches (i.e., the social and political studies on science and technology, global and diplomatic history, economic and institutional history, environmental history and history of science). This lively historiographical scenario has been inspired by certain historical events that have distinguished the economic and technological globalization of the post-Cold War era. These include the willingness of some Western democracies to revive nuclear power generation, while at the same time launching strategies to deal with both decommissioning and radwaste disposal, the increasing global demand for energy, and the growing interest of emerging countries in nuclear power. Meanwhile, climate change has emphasized the need to transition to low-carbon energy systems. Against this overall backdrop, some critical issues continue to persist on nuclear energy. Among these, the most important are those concerning the management of radioactive waste and the location of nuclear facilities, such as reactors and repositories for the disposal of high-level radioactive waste. Considering some case studies, the paper, therefore, aims at providing a historical overview of the efforts that research in the geological sciences has made to address these critical issues.

The historical evolution of the Petrographic (Magmatic) Province idea since the Nineteenth century

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Keywords: petrographic provinces, magmatic associations, igneous rocks.

John Wesley Judd (18 February 1840 – 3 March 1916), a British geologist and fellow of the Royal Society since 1877 and President of the Geological Society between 1886 and 1888, in the late nineteenth century pointed out that «Among igneous rocks of every variety of chemical (and mineralogical, NA) composition, the most highly crystalline types appear to have been formed in those cases only where the liquid magmas have cooled down with extreme slowness and under enormous pressure. Such conditions of slow cooling and great pressure it would seem must have existed when the rock has consolidated at great depths within the Earth's crust; and hence it follows that the highly crystalline rocks now seen at the surface have been exposed through the removal, by denudation, of the vast deposits which originally overlay them. Bearing these principles in mind, it is not difficult to find an explanation of the undoubted fact that the igneous rocks of Tertiary and recent date, as a general rule, exhibit far less perfectly crystalline characters than those which belong to the older geological periods. Cæteris paribus, the older a deep-seated igneous rock is, the greater will be the chance of its being exposed at the surface, through the removal by denudation of the mass of materials under which it was originally formed (…)». That was the first time that time and petrographic features were considered related to each other and considered to represent an important tool for time definition of the geological events. Nowadays, with scientific and technological evolution most of the information related with consanguinity, epoch and time of evolution, genesis and differentiation are directly acquired using geochemical, geochronological and isotopic tools. Therefore, it apparently seems that the use of petrographic, or magmatic, province became a conceptual terminology most related with the past. However, we believe that in many cases, especially where complexity of the tectonic settings and of volcanic associations are high, due to the geodynamic evolution of a region such as in the Western Mediterranean basin, the use of the concept of magmatic province is still recommended. It helps, indeed, in recognising succession of events and thus to clarify in a simple manner the evolution of magmatic events in relations to geodynamic features.

Bridging science and society: geological plaster reliefs as Interdisciplinary tools between 19th–20th Century

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Keywords: geological relief models, scientific heritage, conservation.

Geological models, three-dimensional plaster reliefs made from geological maps between 19th and the 20th century, represent a scientific and artistic heritage that deserves to be emphatized since they represent a key moment in the history of scientific communication, offering effective tools for representing the complexity of the territory before the advent of digital modelling. From a technical perspective, they are configured as multi-material structures: main body is plaster, integrated by metal and wooden elements; the surface, often polychrome, is completed by paper labels with toponyms, to facilitate the reading of the areas of highest interest.

This contribution, developed as part of a PhD interdisciplinary project in Heritage Science, inspired by the study conducted by ISPRA (Fulloni, 2012) and intends to reconstruct the historical parabola of these instruments, analysing some specimens preserved at the Regional Museum of Natural Sciences (Torino, Italy) and the 'Leonardo da Vinci' National Museum of Science and Technology (Milano, Italy).

Geological models have their roots in ancient traditions, before becoming popular in the 19th century, due to the development of modern geological cartography. The introduction of contour lines, the invention of photography and the increase in scientific interest in the field of geology, gave an important impulse to the art of modelling models, which represented at the time the most avant-garde system of morphological representation of the territory.

Personalities such as Felice Giordano (1825-1892), director of the Royal Geological Survey of Italy, and Quintino Sella (1827-1884), promoter of scientific education, recognised their educational and political value, using them both in universal exhibitions (Paris 1878, Anversa 1885) and to make decision-makers aware of the economic potential of the territory (Pantaloni, 2011).

Through the survey of historical sources such as Bollettino della Società Geografica Italiana and Bollettino del Regio Comitato Geologico between the 19th the 20th century, the intention is to reconstruct, whenever possible, the contexts of use and institutional trajectories of these models. A number of emblematic case studies by most important artisans of the time, including Domenico Locchi and Amedeo Aureli (e.g. 'La Provincia di Napoli e sue Adiacenze' (Cossino, 2016), 'Dintorni di Roma', 'Plastico del Garda e della Valle del Brenta') are discussed, with a focus on their practical applications: i) education, as essential tools in a pre-photographic era; ii) industrial politics, as means to promote the exploitation of resources; iii) military context, as models for topographical training.

Urgent systematic cataloging of these often-undocumented artifacts, preserved in suboptimal conditions, is required. We propose rethinking these models as "bridges" between expert knowledge and public understanding: a paradigm still relevant for contemporary science communication and public engagement.

Cossino M. (2016) - Studio e restauro di un plastico polimaterico in gesso dipinto: Il "rilievo geologico della provincia di Napoli e sue adiacenze" di Domenico Locchi. Tesi di Laurea Magistrale in Conservazione e restauro dei beni culturali. Università degli Studi di Torino.

Fulloni S. (2012) - I Plastici Storici del Servizio Geologico d'Italia, Catalogo ISPRA, Servizio attività museali, Dipartimento attività bibliotecarie, documentali e per l'informazione, Roma 2012.

Pantaloni M. (2011) - La carta geologica d'Italia alla scala di 1:1.000.000: una pietra miliare nel percorso della conoscenza geologica. In Uomini ragioni: i 150 anni della geologia unitaria; Sessione F4-Geoitalia 2011, VIII forum italiano di Scienze della Terra, Torino 23 settembre 2011.

The "Montirozzi" of Civitavecchia: A case study of historical documentation of hydrothermal activity

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Keywords: mud volcanoes, Monti della Tolfa, hydrothermal springs.

The area surrounding Civitavecchia, in northern Lazio, offers a compelling example of recent hydrothermal activity, with observations and documentation dating back to the 19th century. Among its most distinctive features are hydrothermal travertine cones, formed by the degassing of CO_2- and H_2S-rich fluids, which are striking elements of the local geomorphology. In this same area, historically known as Torre d'Orlando and now referred to as "Montirozzi", the occurrence of so-called *vulcanetti di fango* (mud volcanoes) was documented by Adolfo Klitsche de la Grange, who described several small "mud volcanoes" formed in 1878, emitting sulfurous vapors and, at times, warm, mineral-laden water (De Rossi, 1883). Klitsche compared these cones "*composed of alternating layers of travertine and sulfate deposits*" to scaled-down *maccalube*, emphasizing both their intermittent activity and their morphological similarity to eruptive cones. His fieldwork represents one of the first systematic accounts of hypothetical low-temperature sedimentary volcanism in Central Italy.

Subsequent surveys reported a progressive decline in hydrothermal activity and the apparent disappearance of the mud volcanoes (Biasutti, 1911). These studies also described inactive travertine cones with distinct stratified geometries and signs of vent migration (Neri Scerni, 1951).

Today, these cones, which are likely aligned along fault or fracture systems, still rise a few meters above a plain characterized by a persistent sulfurous odor, a reminder of the scattered sulfur springs that remained intermittently active until at least the 1990s. This continued activity is supported by localized waterlogging and encrustations on objects and debris dating from that period.

Interestingly, none of the cited authors explicitly identify the travertine cones as the same mud volcanoes described by Klitsche de la Grange. However, the geographical correspondence and the renaming of the site from *Torre d'Orlando* to *Montirozzi* strongly suggest they may be the same features. Ongoing analyses for the realization of Sheet 363 *Civitavecchia* of the Geological Map of Italy at 1:50,000 scale (CARG Project) may help resolve this intriguing historical and geological question.

Biasutti R. (1911) - La cosiddetta salsa della Torre d'Orlando. Rivista Geografica Italiana, 17, 258-259.

De Rossi M.S. (1883) - Presentazione di un suo opuscolo e di due lettere dell'Ing. Adolfo Klitsche de la Grange sopra recenti eruzioni nei vulcanetti di fango presso Civitavecchia. Atti della Pontificia Accademia de' nuovi Lincei, 38, 127-130.

Neri Scerni (1951) - I Montirozzi presso Civitavecchia. Bollettino della Società Geografica Italiana.

Communicating and representing geological phenomena in the Italian journals between 18th and 19th centuries

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Keywords: history of geology, communication, 18th-19th centuries.

Within the early forms of communication of science expressed by Italian journals and periodicals from the 18 Century to the middle of the 19th Century, particular attention was given to catastrophic phenomena such as volcanic eruptions, earthquakes, landslides, and other natural events identified within the new scientific disciplines of the Earth sciences. . The research has taken into account both scientific periodicals and literary / popular journals. The selection of periodicals was primarily headed by their relevance for the history of science communication in Italy, their wide circulation, the journalistic slant and the relevance in terms of "topic coverage", as well as editorial "longevity". The goal is to define how the geological 'catastrophic' phenomena were described in these printed sources, possibly through the use of a specific written and visual language (Rudwick, 1976; Keller 1998; Ciancio & Laurenza, 2018), also with reference to some emerging disciplines within the Earth sciences, such as volcanology and seismology.

Ciancio L. & Laurenza D. (2018) - Visual Representation in Early Modern Earth Sciences, Nuncius, 33, 397-414.

Keller S.B. (1998) - Sections and Views: Visual Representation on Eighteenth-Century Earthquake Studies. British Journal for the History of Science, 31. 129-159.

Rudwick M.J.S. (1976) - The Emergence of a Visual Language for Geological Science 1760–1840. History of Science, 14, 149-195.

Marginalized and obscured, yet pioneering, inspiring and revolutionary: the legacy of Mary Anning

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Keywords: paleontology, Anning, fossils.

Mary Anning (1799–1847) emerged as a pioneering figure in 19th-century palaeontology, despite her humble origins and the gender-based barriers that relegated her to the margins of the scientific community. This work explores the paradox of her existence: a self-taught fossil collector, often overlooked by the male-dominated establishment, who nonetheless made discoveries that fundamentally reshaped our understanding of prehistoric life.

Through an analysis of her groundbreaking finds, including ichthyosaurs, plesiosaurs, and one of the first complete skeleton of a pterosaur (*Dimorphodon*), we highlight how her scientific insights and meticulous observation laid crucial foundations for modern palaeontology. Her dedication, along with a deep, largely self-taught knowledge of comparative anatomy, earned her quiet respect among contemporary scientists, even if public recognition remained elusive. Her contributions were instrumental in transforming palaeontology from a hobbyist pursuit into a rigorous scientific discipline.

Finally, Anning's legacy extends to the origins of paleoart as we know it today. Her fossil discoveries inspired the first scientifically grounded reconstructions of prehistoric life. A key example is Duria Antiquior, a painting by Henry De la Beche based on Anning's specimens, which is widely regarded as the first visual depiction of a prehistoric scene derived from fossil evidence.

Historical perspectives and roots of geological studies in the Red Sea area by Arturo Issel (1842–1922)

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Keywords: history of geology, Arturo Issel, Red Sea.

Arturo Issel (1842–1922), Professor of geology and mineralogy at the University of Genoa (Italy), was a central figure in the cultural society in Genoa of his time, belonging to a positivist elite who aimed to establish a new culture for the new unified state of Italy. He was well-known both nationally and internationally as a geologist but also as a geographer and scientific traveller being one of the founding members of the Italian Geographical Society established in 1867. He contributed in particular to the scientific knowledge of the Red Sea area taking part in two significant voyages: one in 1865 to Egypt and the Red Sea. The second in early 1870, as part of a scientific expedition in the exploration of the Red Sea coastline, Bay of Assab (Eritrea) and Cheren in the Ethiopian Highlands that lasted five months. The aim of this paper is to discuss and place in context his observations, illustrations and publications related to the Red Sea area arising from his travels and studies (Issel 1869, 1872, 1899).

Issel A. (1869) - Malacologia del Mar Rosso: Ricerche zoologiche e paleontologiche. Pisa: Editorie della biblioteca Malacologica.

Issel A. (1872) - Viaggio nel Mar Rosso e tra i Bogos. Milano: Fratelli Treves.

Issel, A. (1899) - Essai sur l'origine et la formation de la Mer Rouge. Bulletin de la Société belge de géologie, de paléntologie et d'hydrologie, 13, 65-84.

The difference between a sceptic and a negationist. The CO_2 business and the role of geologists in a greener future

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Keywords: global warming, CO_2, energy.

The role of CO_2 in forcing the outgoing longwave radiation grabs maximum attention for more than three decades. The mainstream is dictated by the IPCC reports, whose monolithic message points to the necessity of CO_2 decrease. Following this approach, IPCC invites worldwide economies to ally in a mitigation war, aiming to reach carbon neutrality before 2050. The transition to a decarbonized society is certainly one of the priorities we have to deal with. It is certainly possible, but only if we accept a long-lasting and painful degradation of our life styles. None of the OECD politicians would have ever dare to clearly state this, because this would imply no election to the next call to the pools.

Discussions on the energy transition can be grouped in two main reasoning styles. The first, by far the most widespread, is of conspiracy-type, and considers the possibility of moving to a decarbonized world immediately as a real thing, hindered only by oil lobbies and old-style oil industrialists (e.g., Jacobson, 2023). The other view considers, with a greater dose of realism, that the energy transition is extremely difficult, very expensive and certainly impossible to achieve except in a few decades of gradual adaptation (e.g. Smil, 2022).

To simply doubting that ~0.01 mass % of CO_2 increase in the atmosphere in the last 250 years represents the only cause of global warming allows a person to be considered as a non-scientist, or a scientist on the payroll of fossil energy lobbies. Is the role of a scientist incompatible with a sceptical approach on CO_2? Is CO_2 the real responsible of global warming, or are there other parameters we should take into account? How far a scientific temperature coverage can be extended, considering that the first global measures started officialy in the occasion of the 1958 Geophysical International Year? Are the global warming consequences 100% negative? Renewable sources will never be able to satisfy lifestyles of rich countries because they are intermittent, inconstant, have poor energy density and cannot be stored in sufficient quantities. Our priority should be the availability of matter, which is transformed through renewable energy into the objects of our desires. The main target of modern societies should be not only to abandon fossil sources of energy, but simply to consume less. To consume less means to lower life standards, higher unemployment rate and work with more sweat. It is not only a matter of low-carbon energy availability. Our worries would be to find sufficient matter (in particular metals) to be transformed into our desires. The role of geologists on this topic is and will remain fundamental.

Jacobson M.Z. (2023) - No miracles needed. How today's technology can save our climate and clean our air. Cambridge University Press, 454 pp.

Smil V. (2022): How the world really works - A Scientist's Guide to Our Past, Present and Futur. Viking Press, 336 pp.

Valerius Faventies' *De montium origine* (1561): a dialogue on the origin of mountains

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Keywords: history of geology, Valerius Faventies, orogenic theories.

The speculations on the origin of Earth's geological shape *sensu latu* has stimulated the interest of philosophers at least since Aristotle, who in his *Meteorologica* sets out his theories on the relationships between the elements common to air and water, as well as the types and parts of the Earth and the physical phenomena developing inside the earthly sphere, according to the geocentric model. For Aristotle, as well as for Seneca and Pliny, the study of the mountains was aimed to clarify the origin of rivers, earthquakes and volcanic phenomena.

At the beginning of the modern era, the Dominican friar Valerius Faventies published a booklet that investigated the natural phenomena and the possible causes of the origin of mountains (*De montium origine*, 1561), a work inspired by the well-known 13th Century Italian treatise *La composizione del mondo colle sue cascioni* (the composition of the world with its causes) by Ristoro d'Arezzo (Romano, 2023). The booklet reports a dialogue between two gentlemen, Rodulphus and Camillus, during a leisure time (*otium*) in a countryside villa nestled on the shores of the Garda Lake, in Italy, near the town of Garda, in front of towering mountains plunging steeply into the lake.

Valerius Faventies (1525? – 1598) was born in Verona to a wealthy family whose founder was a captain of fortune who emigrated from Faenza (*Faventia*) in the early 15th century. He lived for a long time in Venice, where he was a member and theologian of the *Accademia Venetiana* (or *Accademia della Fama*), whose printing house published his *De montium origine*. This work collects the theories formulated by classical authors on the nature of mountains and landmasses in the context of world history and the orthodoxy of the Catholic Church. An expert scholar grown in classical culture, Faventies summarizes the theories and hypotheses on the origin of mountains collected in Greek, Latin and medieval sources. However, his approach is not that of a leading innovator, at least in terms of the development of original concepts: in fact, the speculations that marked a fundamental change in the interpretation of the nature of geological strata were formulated only later in Nicholas Steno's *Prodromus* (1669).

Faventies failed to create logical connections between the various theories, nor did he draw conclusions that could be used for field testing: he is neither an observer nor an experimenter. Nothing is interpreted through direct observations of nature. Georgius Agricola, who had already used the method of direct observation of geological objects, remains a dead letter. Faventies seems not to know Agricola's works, or deliberately does not cite them, even if he uses the discussions on "underground phenomena" reported in *De ortu et causis subterraneorum* (Agricola, 1546). However, Faventies managed to collate in good order most of the knowledge handed down through the works of classical authors on the origin of the mountains with an uncommon clarity of exposition.

Agricola G. (1546) - *De ortu & causis subterraneorum Lib. V. De natura eorum quae effluent ex terra Lib. IIII. De natura fossilium Lib. X. De veteribus & novis metallis Lib. II. Bermannus, sive de re metallica dialogus. Interpretatio Germanica vocum rei metallicae, addito Indice foecundissimo*. Basel, Froben.

Faventies V. (1561) - *De montium origine*. In Academia Veneta. (Italian translation in: Faenzi V. (2006) - Sull'origine delle montagne. Testo a fronte a cura di Paolo Macini e Ezio Mesini, prefazione di Georges Cottier, note al testo di Maria I. Campanale. Verbania, Tararà, 178 pp.

Romano M. (2023) - Geological elements in the in thirteenth-century treatise "La Composizione del Mondo" (The composition of the World) by Ristoro d'Arezzo. Ital. J. Geosci., 142(2), 217-243, https://doi.org/10.3301/IJG.2023.13.

Steno N. (1669) - *De solido intra solidum naturaliter contento, dissertationis prodromus*. Florentiae, Typ. sub signo Stellae.

Ramazzini's geological field trip to the oil springs of Montegibbio (1698)

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Keywords: petroleum history, Bernardino Ramazzini, hydrogeology.

The Italian physician and naturalist Bernardino Ramazzini (1633-1714) is known in the field of hydrogeology for his annotations and studies concerning the nature of underground water and the interpretation of the origin and hydrodynamics of confined aquifers (1691), which were commonly exploited in his homeland, the Pleistocene alluvial plain north of Modena (Italy). He neither coined nor used the term "confined" or "artesian", the latter a term that emerged in the early 19th century in France, where many wells were being drilled in the Artois region. He conceived and depicted a physical model of this phenomenon, which he attributed to the principle of communicating vessels. Later, he extended his scientific interests to geologic and stratigraphic issues and published the first hydrogeological cross-section highlighting the relationship between different hydrostratigraphic units. He also anticipated the studies on atmospheric electricity, air temperature and pression measurement, perfectioning the Torricelli's mercury barometer, and investigated the natural history of the crude oil seepages occurring in the Apennines of Modena.

Since the Middle Ages, this precious *olio di sasso* (*oleum petrae*, i.e., *petroleum*) was actively extracted from shallow hand-dug wells or skimmed from natural seepages and salt springs (Macini & Mesini, 2019). In 1690, G.W. von Leibniz visited Modena and spent many days with Ramazzini, appreciating his studies and scientific methodology, based on the experimental practice. However, his primary interests were in the field of medicine, and he actively practiced as a doctor. In 1700 he published his masterpiece *De morbis artificum diatriba* (On the diseases of workers, 1700), which remained for over two centuries the main reference for the epidemiological study of occupational diseases, translated into many languages. Following the teaching of Hippocrates, he coined the motto *longe praestantius est praeservare quam curare* (prevention is better than cure), making him the father of occupational medicine.

His passion for natural observations and the study of historical sources persuaded him to publish a critical edition of Ariosto's study on the oil springs of Modena (1698), adding in the appendix a letter addressed to Felice Viali, professor of botany at the University of Padua. Here Ramazzini explains the reasons that led him to study Ariosto's work, adding personal observations on the field operation of oil extraction at Montegibbio, a village in the Apenninic foothills south of Modena that he visited, taking Ariosto's book with him as a travel guide. He knew the dangerous drilling techniques for the construction of water wells, and his *De morbis* contains a chapter on the health of water well diggers (*putearii*). It is not unlikely that Ramazzini's trip to Montegibbio was also aimed to examine his patients in their workplace, convinced that he could better identify the etiology and pathogenesis of occupational diseases in person.

Ariosto F. (1698) - Francisci Ariosti de oleo montis Zibinii, seu petroleo agri mutinensis libellus. Mutinae, Capponi.

Ramazzini B. (1691) - De fontium mutinensium admiranda scaturigine, Tractatus physico-hydrostaticus. Mutinae, Suliani.

Ramazzini B. (1700) - De morbis artificum diatriba. Mutinae, Capponi.

Macini P. & Mesini E. (2019) - La fortuna del petrolio di Montegibbio da Francesco Ariosto all'epoca moderna. Atti Soc. Nat. Mat. Modena, 150, 35-75.

Scrope and his contribution to the Italian Nineteenth-Century Volcanology

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Keywords: history of volcanology, history of geology, history of science.

The English economist and volcanologist George Julius Poulett Scrope (1797–1876) was introduced to geological sciences at Cambridge by Clark and Sedgwick. He soon started to travels in Italy where he observed and studied numerous volcanoes. Initially focusing on Vesuvius and the Phlegraean Fields, and later extending his research to the Aeolian Islands and Mount Etna. He further expanded his studies to other volcanic regions in Italy, as well as to the Auvergne region in France and the Eifel region in Germany. Scrope published the first systematic treatise on volcanoes: "Considerations on Volcanoes" (Scrope, 1825).

He worked in the geological field when Werner's Neptunist theory was still predominant, yet he actively contributed to its overcoming. His scholarly interests also included the formation of river valleys, and regarding the Earth's formation, Scrope adopted the notion of gradual cooling from an initially hot and fluid planetary body. He criticized the theory of uplift crater hypothesis, a theory widely supported by prominent scholars such as Humboldt, von Buch, and others of the time.

From the institutional point of view, Scrope form the 1824 was an influential member of the Geological Society and he became one of its secretaries the following year, sharing this role with Lyell and, in 1867, he was awarded the Wollaston Medal by the same society. While Scrope developed many of his key volcanological ideas in Italy, there is a lack of comprehensive studies on his work in the Italian language. The sources that have brought attention to his studies and publications are predominantly in English (Rudwick, 1974).

This paper aims to delve into the specifics of Scrope's hypotheses and theories, integrating his research into the broader context of nineteenth-century geovolcanology. In particular, it will address the major investigations undertaken by both Italian and international scholars in the first half of the nineteenth century, focusing on active volcanic areas in Italy such as Vesuvius, Aeolian Islands, and Mount Etna.

Rudwick M.J.S. (1974) - Poulett Scrope on the volcanoes of Auvergne: Lyellian time and political economy. British Journal for the History of Science, 7, 205-242.

Scrope G.J.P. (1825) - Considerations on volcanos, the probable causes qf their phenomena, the laws which determine their march, the disposition of their products, and their connexion with the present state and past history of the globe: leading to the establishnment of a new theory of the earth. Phillips, London, 270 pp.

Visions. The Earth Sciences in the popular literature of the 19th Century

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Keywords: history of geosciences, visual culture.

The 19th century was marked by major scientific discoveries and, as a result, by an unprecedented wave of popular science communication. Earth sciences—especially geology and paleontology—were particularly well suited to this new visibility, and, above all, to being illustrated. The first half of the century was characterized by the publication of textbooks and fieldwork accounts, mostly intended for engineers, scientists, and students—for example, Charles Lyell's *Principles of Geology* (1830). While many savants were working on the first geological maps (such as the 1841 map of France), intense debates arose over the age of the Earth, fueled by the research of Charles Darwin, Georges Cuvier, and Alexandre Brongniart.

This scientific ferment led to a spectacular surge in the popularization of Earth sciences and of a previously little-known subterranean world, particularly from the 1850s onward, with the advent of world's fairs and the proliferation of popular science publications—magazines, educational books, and even novels such as Jules Verne's *Journey to the Center of the Earth* (1864). These texts were invariably accompanied by rich visual materials. A close examination of these images reveals the gradual development of a new visual language designed to communicate Earth science knowledge to a broader audience. On one hand, these illustrations were rooted in the more technical iconography of scientific manuals; on the other, they reflected trends in contemporary art, such as Romantic landscape painting and social realism.

Situated between the history of art and the history of science, this paper will explore the creation of a renewed iconography of the Earth sciences and the emergence of a new visual language, shaped through collaborations among artists, geologists, engineers, publishers, and popular science writers.

The communication studies this new visual language while taking into account a specific case study, the exhibition *Visions. The Earth Sciences in the popular Literature of the 19th Century* (Varese, Italy, November-December 2023), that will also allow to open the perspectives on the contemporary visual and scientific communication of Earth sciences and their history.

A historical attempt to reconstruct the excavations of Ypresian Pesciara and Monte Postale sites (Bolca, northeastern Italy)

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Keywords: Bolca, Pesciara, Lower Eocene.

The lower Eocene (Ypresian) fossil sites of Pesciara and Monte Postale, located near Bolca in the Lessini Mountains, are globally renowned Cenozoic *Konservat-Lagerstätten*. Since the 16th century, Bolca and its fossils have played a pivotal role in philosophical and naturalistic discussions, which, despite over four centuries of inquiry, remain unresolved.

This presentation aims to trace the historiographical development of the excavations that have unearthed the fossils of Bolca. Over the course of more than four centuries, the iconic Pesciara site has undergone significant changes, as evidenced by the disappearance of some fossiliferous layers, while the Monte Postale site has been the focus of more recent paleontological research, particularly from the 19th century onward.

The history of these excavations is closely intertwined with the geography of the region, as depicted in ancient maps of the sites. It is also shaped by the historical events and scholarly debates that have engaged early researchers, such as Giovanni Arduino (1714–1795), Antonio Vallisneri (1661–1730), Giovanni Serafino Volta (1754–1842), and Scipione Maffei (1675–1755), as well as more recent scholars, including Jacques Blot (1924–1988), Lorenzo Sorbini (1939–1997), and the Cerato family, who have been actively involved in the site's excavations for over two centuries.

The fossil as evidence: Paolo Boccone and the emergence of naturalistic explanation

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Keywords: history of geology, Steno, *Glossopetrae*.

Paolo Silvio Boccone was a 17th-century Italian naturalist whose diverse contributions to natural sciences, particularly in botany, geology, and palaeontology, warrant renewed attention. Born in Palermo in 1633 (though some suggest Sciacca), Boccone was a member of a noble Ligurian family and was educated in various Italian cities before becoming a Cistercian monk under the name Silvio. A student of Pietro Castelli, Boccone was active within intellectual circles, including figures such as Agostino Scilla and Giovanni Alfonso Borelli. Through extensive travel across Europe (1670–1698), Boccone built a network of scientific correspondents and gained firsthand exposure to diverse fossil and mineral specimens. This contribution explores Boccone's palaeontological legacy, highlighting his role in the early debate on the organic versus inorganic origins of fossils. Boccone strongly advocated for an organic interpretation, directly opposing theories of spontaneous mineral formation. His writings, particularly *Recherches et Observations Naturelles* (1674), *Osservazioni Naturali* (1684), and *Museo di Fisica e di Esperienze* (1697), present detailed analyses of fossil corals, echinoids, molluscs, and shark teeth ("*Glossopetrae*"). He employed empirical comparisons with extant marine organisms and used illustrations to support his interpretations. Of particular note is his nuanced understanding of fossilisation processes and paleoenvironmental change. Boccone correctly inferred marine transgressions from fossil coral distributions and described phenomena such as earthquakes and tsunamis with surprising accuracy. His critical approach, observational rigour, and openness to emerging ideas, such as those of Steno, establish him as a significant, though underappreciated, contributor to the foundational period of palaeontology and historical geology.

From curiosity cabinet to 'scientific' method: the palaeontological legacy of Ferrante Imperato

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Keywords: history of palaeontology, naturalistic cabinet, meaning of fossils.

This contribution examines the paleontological content of *Dell'Historia Naturale* (1599), a seminal work by Italian naturalist Ferrante Imperato (1550–1625), which represents a foundational work in the history of natural sciences. Imperato established one of the earliest natural history cabinets in Naples, which served both as a prototype for modern museums and a hub of intellectual exchange. His empirical methodology, based on direct observation and experimentation, distinguished his approach from many of his contemporaries. Among Imperato's most significant contributions was his correct interpretation of fossils as the remains of once-living organisms, at a time when many scholars considered fossils to be inorganic "figured stones," or simply 'jokes of nature'. He also demonstrated an advanced understanding of fossilisation processes, accurately describing internal and external moulds and the process of fossil silicification. Although some of his interpretations, such as those of durophagous fish teeth ("*Bufoniti*") or belemnites ("*Lincurio*"), were less precise, his investigative rigour and use of experimental methods were pioneering for the period. Imperato also contributed to early geology by providing one of the first detailed descriptions of a stratigraphic section near Naples and by correctly associating the inland presence of marine fossils with historical changes in sea level. Imperato's extensive network of scholarly correspondents helped shape an emerging scientific community. While his legacy has often been overshadowed by more widely recognised figures, his work laid essential groundwork for the development of modern palaeontology and geology.

Early investigations on Italian coal deposits: Giovanni Fabbroni's geological and mining studies in Tuscany (1790)

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Keywords: coal deposits, coal mining, steel industry.

Giovanni Fabbroni (Firenze 1752 – Pisa 1823) was a naturalist, chemist, agronomist and economist active in many institutions and in the technical administration of the Grand Duchy; he was a founder and vice director of the Natural History Museum in Florence. Member of the *Accademia dei Georgofili* since 1783, his predisposition for languages (indeed, his mother was German) made him one of the most cosmopolitan intellectuals of the late 18th century Tuscany. Between 1775 and 1780 the government sent him on a long trip abroad, and he lived in Paris and London, carrying out research in the field of arts and manufactures, mines and agriculture, and establishing long lasting contacts with the leading scientists of the continent. Living in Paris during the years of the revolution of the chemical studies of Lavoisier, of whom he was a supporter, he collaborated with the chemist Rouelle; later, in London he wrote the notes to the English version of Cronstedt's system of mineralogy (1788). In 1779 he travelled through the northern counties of England, visiting coal and metal mines, steelworks, cannon factories, spinning mills and dyeing plants; here he observed and studied the manufacture of steel, porcelain, the industrial production of sulphuric acid and the new machines for the textile industry, and was impressed by the new steam engine of James Watt, which he suggested for reclaiming the marshes of Maremma and the exploitation of deep mineral deposits in Versilia. His notebooks formed the basis for his work as technical and mining consultant to the Habsburg-Lorraine in Tuscany.

Here Fabbroni supported the reforms of Pietro Leopoldo I and in 1790 wrote his geological and mining studies on coal (1790). Later, Ferdinand III gave him several public offices, which he kept and increased during the Napoleonic period and the Restoration, when he became responsible of the Grand Duchy's mines. He was appointed "Royal Commissioner to the Joint Council for the administration of the iron mines in Elba and for the control of the *Magona* Toscana", and more generally he was asked to contribute to the improvement of the Tuscan economy, also through the identification of potentially profitable coal deposits.

His essay on coal was commissioned by the government. Here he examines the characteristics of Anthracite, its various qualities and reports its chemical analysis. He discusses the possibility of finding good quality coal in Tuscany, the stratigraphy, depth and orientation of coal seams, not forgetting the issues of preliminary investigations (possibly carried out by means of exploration drilling from the surface) and the opportunity of opening new mines with the most recent mining techniques. Finally, he evaluates the comparative advantages of capital and technology investments in the coal industry. The question of Italian coal deposits was largely rationalized only one century later (Corpo Reale delle Miniere, 1893), with a general survey of the Country's resources.

Corpo Reale delle Miniere (1893) - Rivista del servizio minerario nel 1891. Roma, Bertero.
Cronsted A.F (1788) - An Essay towards a system of mineralogy, ... translated from the original Swedish. London, Dilly.
Fabbroni G. (1790) - Dell'Antracite o carbone di cava detto volgarmente carbone fossile. Compilazione fatta per ordine del Governo. Firenze, Cambiagi.

Paolo Gorini's public experiment on volcanoes formation (1872)

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Keywords: volcanology, experiments, P. Gorini.

Paolo Gorini (1813-1881) was an eclectic Italian scientist, a brilliant scholar self taught in natural sciences with interests in fisiology, biology, chemistry and in particular geology. He is known mainly for his theoretical and experimental contributions to the scientific study and practices of conservation of anatomical specimens and corpses (petrification), as well as on their dissolution, mainly through cremation. However, one of Gorini's main and still little known interests concerned the formation of mountains and volcanoes (Gorini, 1851), which he referred to the action of "plutonium", a primordial molten matter containing gaseous parts in its mass, whose explosions would have determined, with the rupture of the Earth's crust, the orogenetic phenomena such as the "growing" of mountains. Gorini dedicated most of his time to what he called "experimental geology", which he carried out in particular with "plutonic" or "volcanic experiments", mainly in his private laboratory, about the reproduction of eruptive dynamics on small scale, using artificial models of volcanoes (Gorini, 1871). He also organized public demonstrations and was invited by universities, scientific societies and popular science associations, (mainly in northern Italy) to present his "volcanic experiments" (Gorini, 1872). These were rather popular among the general public, which became emotionally involved in the spectacular demonstrations and fascinated by the idea that volcanic eruptions and even earthquakes could be predicted with the use of Gorini's methods. The aim of this paper is to present and analyze the public experiment which Gorini performed in Genoa on May 12, 1872 and was described by geologist Arturo Issel.

Gorini P. (1851) - Sull'origine delle montagne e dei vulcani. Studio sperimentale. Lodi, Wilmant.
Gorini P. (1871) - Sull'origine dei vulcani. Studio sperimentale. Lodi, Wilmant.
Gorini P. (1872) - I vulcani promessi a Milano nel 1868. Lodi, Wilmant.

S36.

Understanding provenance and processing of geomaterials in archaeological Heritage through mineralogy and petrography: from microscope and geochemistry to AI

Conveners and Chairpersons

Fabrizio Antonelli (Università Iuav di Venezia)

Emma Cantisani (CNR, Firenze)

Giacomo Eramo (Università di Bari Aldo Moro)

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Provenancing ancient metals by lead isotope analysis – State of the art

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Keywords: lead isotope analysis, metal provenancing, LIA databases.

Lead isotope analysis (LIA) is a routine tool for dating rocks and geological processes. Recently it has also found extensive application in the environmental sciences. In the mid-sixties it was also proposed that LIA could be used to provenance ancient metal artefacts (mainly copper, bronze, silver, lead) in order to link artefacts and original ore deposits, based on the fact that the lead isotope ratios were observed to remain unchanged during the reducing/smelting processes of metals from the ores and the subsequent metallurgical processes. Although conceptually correct, the application of the method met with alternate fortunes and credibility because of historical contingencies, partly wrong applications, and especially the lack of extensive databases (Artioli et al., 2020; Killick et al., 2020). The historical application of LIA to archaeological objects will be briefly reviewed, with a focus on the reference databases which are presently under development and the currently adopted interpretation methods and strategies (Baron et al., 2014; De Ceuster et al., 2023).

Artioli G. et al. (2020) - LIA of prehistoric metals in the Central Mediterranean area: A review. Archaeometry, 62(S1), 53-85, https://doi.org/10.1111/arcm.12542.

Baron S. et al. (2014) - How Mineralogy and Geochemistry Can Improve the Significance of Pb Isotopes in Metal Provenance Studies. Archaeometry, 56(4), 665-680, https://doi.org/10.1111/arcm.12037.

De Ceuster S. et al. (2023) - Lead isotope analysis for provenancing ancient materials: a comparison of approaches. RSC advances, 13(28), 19595-19606, https://doi.org/10.1039/D3RA02763E.

Killick D. et al. (2020) - Geological constraints on the use of lead isotopes for provenance in archaeometallurgy. Archaeometry, 62(S1), 86-105, https://doi.org/10.1111/arcm.12573.

Microstratigraphic reconstruction of the preparatory mortars of the Alexander Mosaic (Battle of Issus, National Archaeological Museum of Naples)

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Keywords: mortars, Alexander Mosaic, archaeometry.

This contribution provides the results of a comprehensive stratigraphic, mineralogical, and petrographic investigation of the mortars and other materials forming the backing layers of the so-called Alexander Mosaic (Battle of Issus), currently hosted in the National Archaeological Museum of Naples. The aim of this study was to define the nature and structural integrity of this part of the mosaic, essential for its support, aimed at the restoration of the entire artwork, which is currently in progress. The Alexander Mosaic is composed of approximately 1.6-1.9 million tesserae, predominantly of carbonate stones, set into a ~1 cm thick *supranucleus* made of aerial lime mortar with fine multicolored aggregates (Balassone et al., 2025). Compositional data of the various mortar layers were obtained from microsampling and combined mineralogical and petrographic analyses and allowed a detailed reconstruction of the mosaic's stratigraphy, from the surface tesserae layer to the gypsum-based integration added in 1916-1917.

The *nucleus* consists of a ~3 cm thick white aerial lime mortar layer with predominantly carbonate aggregate with an estimated weight of ~1.0 ton. This layer exhibits various interventions, including localized consolidations with rosin at the lower edge, green-pigmented gypsum at the upper edge, and a poorly preserved lime mortar with volcanic aggregate along the upper edge. The *rudus* (~9 cm thick, 2.4–2.7 tons weight) is a highly hydraulic lime mortar enriched with crushed brick and volcanic fragments, ensuring greater mechanical strength and cohesion. Below the *rudus* lies a pozzolanic lime mortar with lightweight volcanic aggregate (pumice), likely the remains of a bedding layer originally used in the peristyle of the House of the Faun in Pompeii. This interface may have served as the separation plane during the 1843 detachment. A notable discontinuity between the *nucleus* and *rudus* along the mosaic's perimeter and likely extends inward was observable even upon a macroscopic inspection, caused by volumetric shrinkage during carbonation of the aerial lime, resulting in delamination from the *rudus*. This gap appeared to host secondary gypsum crystallization phenomenon.The final layer, applied during the 1916–1917 relocation of the mosaic within the museum, consists of highly tenacious gypsum (98%), corresponding to an estimated weight of 1.1 tons.

The Alexander Mosaic displayed the multi-layered construction technique typical of ancient craftsmanship, which has ensured its preservation over centuries. The most critical vulnerabilities identified in this study have been exhaustively reported, as part of the assessments related to a proper reworking of the backing side of the mosaic.

Balassone G. et al. (2025) - From tiny to immense: Geological spotlight on the Alexander Mosaic (National Archaeological Museum of Naples, Italy) using non-invasive in situ analyses. PLoS ONE, 20(1), e0315188, https://doi.org/10.1371/journal.pone.0315188.

Multi-analytical characterization and provenance assessment of Oenotrian pottery raw materials (Basilicata region, Southern Italy)

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Keywords: ceramic artifacts, archeometry, provenance assessment.

Several ceramic fragments from three sites of the Oenotrian culture were analysed using a multi-analytical characterization and archeometric techniques such as X-ray diffraction and scanning electron microscopy (SEM-EDS). It is well known that ceramic artefacts were made by using clay materials, therefore, this study aimed to assess the provenance of the natural raw materials used for the production of artifacts found in three Oenotrian sites (Anzi, Garaguso and Brindisi di Montagna) (Monaco & Donnici, 2021; Donnici & Pecci, 2025) by analysing their mineralogical and chemical composition. A total of twelve samples of natural clay materials were collected in the Anzi Calvello basin (ACB), in the vicinity of Anzi and Calvello centres, to observe a similarity in mineralogical and chemical composition with the Oenotrian ceramic sherds from the same basin (ACB). The results of mineralogical XRPD analysis and SEM-EDS analyses indicated that the mineralogical composition is quite similar for all samples, mainly consisting of quartz and calcite, and a lesser abundance of clay minerals. The compositional data revealed that the mineralogy of both clays and sherds is dominated by Al2O3 and CaO, with less abundance of SiO2 and Fe2O3. The compositional comparison between the clay samples and the ceramic sherds shows some differences in the relative abundances of Al2O3 and CaO, which are higher in the ACB clay samples. This suggests that the raw materials used for the pottery from the three sites are not related to the ACB clays and that their provenance is more associated with the clays of the Bradanic Trough. Likely, the clays used to produce the pottery found at the three Oenotrian sites came from three different locations in the Bradanic Trough, possibly from the north-western part of the ACB, where the clays show a lower carbonate content, since higher abundances of calcite may limit the use of clays in pottery and therefore clays with lower CaO values are more suitable for ceramic production.

Donnici F. & Pecci A. (2025) - Nuove indagini archeologiche nel sito enotrio di loc. Raia (Anzi, PZ). SIRIS, 23, 167-179.

Monaco M.C. & Donnici F. (2021) - Ritorno ad Anxia. Ricerche archeologiche in un territorio della Lucania interna, Erreciedizioni.

Towards interpretable deep learning in ceramic petrographic fabric classification through a comparative study of convolutional neural networks and vision transformers

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Keywords: Levantine ceramics, deep learning, explainable Artificial Intelligence.

In recent decades, there has been growing interest in the application of Artificial Intelligence (AI) to archaeology and archaeometry, where it shows promising potential in addressing specific research challenges and supporting complex analytical tasks. Among these, an innovative development is represented by the application of Machine Learning (ML) and Deep Learning (DL) models for ceramic analysis. Recent studies have indeed demonstrated their effectiveness in identifying specific compositional, technological, or stylistic patterns (Qi et al., 2022; Ruschioni et al., 2023).

This study explores the use of Deep Learning models for the classification of Levantine ceramic thin sections by identifying distinctive compositional features. A dedicated dataset of ceramic thin section images was built to train and validate the models. The ceramic samples are dated back from the Early Bronze Age to Iron Age and come from several archaeological sites across the Levant including Bethlehem (West Bank), Tell el-Far'ah North (West Bank), Khirbat Iskandar (Jordan), Khirbat al-Batrawy (Jordan), Ebla (Syria), Jericho (West Bank), Tell Nebi Mend (Lebanon), and Tell Qasile (Israel).

This research applies both Convolutional Neural Network (CNNs) and Vision Transformer (ViTs) models to evaluate their performance in classifying ceramics within their petrographic fabrics, which reflect the raw materials used and the production technologies. Additionally, Explainable Artificial Intelligence (XAI) techniques are employed, with the aim of enhancing transparency and interpretability (Zhong et al., 2022). Furthermore, this study investigates the implementation of Adaptive Vision Transformer (A-ViT) and Dynamic Vision Transformer (DynamicViT) architectures, which introduce adaptive token selection mechanisms (Liu et al., 2024). These methods dynamically allocate computational resources by focusing attention on the most informative regions of an image, allowing the models to improve both classification accuracy and efficiency. The use of these advanced transformer-based models, in conjunction with XAI, aims to open new pathways for the application of interpretable deep learning in archaeological science.

Liu Y. et al. (2024) - Dynamic token-pass transformers for semantic segmentation. In Proceedings of the IEEE/CVF Winter Conference on Applications of Computer Vision (pp. 1827-1836), https://doi.org/10.48550/arXiv.2308.01944.

Qi Y. et al. (2022) - End-to-end ancient ceramic classification toolkit based on deep learning: A case study of black glazed wares of Jian kilns (Song Dynasty, Fujian province). Ceramics International, 48(23), 34516-34532, https://doi.org/10.1016/j.ceramint.2022.08.033.

Ruschioni G. et al. (2023) - Supervised learning algorithms as a tool for archaeology: Classification of ceramic samples described by chemical element concentrations. Journal of Archaeological Science: Reports, 49, 103995, https://doi.org/10.1016/j.jasrep.2023.103995

Zhong X. et al. (2022) - Explainable machine learning in materials science. npj computational materials, 8(1), 204, https://doi.org/10.1038/s41524-022-00884-7.

Gray fine ware from Bostel di Rotzo (VI): characterization and provenance study

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Keywords: Bostel di Rotzo, mass spectrometry, provenance study.

The Bostel di Rotzo site (Asiago Plateau, Vicenza) is a key Magrè group settlement from the Second Iron Age (5th-2nd century BCE). Excavations revealed domestic and productive structures, possibly a pottery workshop, and many gray fine ware sherds. While stylistically similar to lowland ceramics, Rhaetic inscriptions point to cultural and material exchange between Alpine and plain communities (Magnini et al., 2019).

This study investigates the composition and provenance of the raw materials used in the ceramic production through Inductively Coupled Plasma-Optical Emission Spectroscopy and Mass Spectrometry (ICP-OES/MS). Multivariate statistical approaches, including Principal Component Analysis and Hierarchical Clustering, were applied to the elemental data using a Sc-based normalization strategy (Dias & Prudêncio, 2008). The preliminary characterization revealed relative compositional homogeneity, except for a small subset of samples which diverged particularly in REEs, Th, U, and Pb, as well as the Si-Al content.

To evaluate the provenance, samples from two local clay sources located in the surroundings of the Bostel area were analyzed. Enrichment Factors (EFs) were calculated for both the archaeological and clay samples, highlighting an overall compositional similarity with the local deposit collected at the Cenge area. This is further confirmed by the results of the multivariate analysis, which supports the probable local provenance of the raw materials for most of the samples.

A regional comparison with published archaeometric datasets showed that samples collected in Bostel di Rotzo tend to separate from other provenance groups (Este and Padova in particular), reinforcing the idea of a local production. The only exception is the small subset already identified during the elemental characterization, which displays similarities to the Este gray wares (Maritan et al., 2005), suggesting a probable importation from the plain. This research was thus able to confirm a local ceramic tradition for gray ware production, which was previously hypothesized only on stratigraphic and contextual basis. Additionally, it further emphasizes the possibility of a broader exchange networks in which the Bostel community was involved.

Dias M.I. & Prudêncio M.I. (2008) - On the importance of using scandium to normalize geochemical data preceding multivariate analyses applied to archaeometric pottery studies. Microchemical Journal, 88(2), 136-141, https://doi.org/10.1016/j.microc.2007.11.009.

Magnini L. et al. (2019) - Multisensor-multiscale approach in studying the proto-historic settlement of Bostel in northern Italy. Archeologia e Calcolatori, 30, 347-365, https://doi.org/10.19282/ac.30.2019.20.

Maritan L. et al. (2005) - Second Iron Age grey pottery from Este (northeastern Italy): study of provenance and technology. Applied Clay Science, 29(1), 31-44, https://doi.org/10.1016/j.clay.2004.09.003.

The marbles of the Roman Thermal Baths of *Teate Marrucinorum* (Chieti, Italy): autoptic, petrographic, mineralogical and geochemical features

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Keywords: archaeometry, marble provenance, Roman baths.

Ancient Romans widely used rocks with great aesthetic attributes to craft sculptures and artifacts, as well as to adorn buildings. They sourced a broad range of ornamental stones from various locations across their domains, according to the popularity and the visual allure of these decorations. From an Earth Sciences perspective, these extensive variety of stones encompasses metamorphic, sedimentary or igneous origin, ranging from simple white marbles to colourful lithotypes. The intensive extraction and the high number of quarries across the whole Empire fostered the development of trade and supply networks for long distances all over the Mediterranean area (Gnoli, 1988).

Mineralogical-petrographic investigation coupled with isotopic analyses are commonly used to determine the provenance of white marbles (Antonelli & Lazzarini, 2015). In contrast, the provenance of polychromes counterparts is usually inferred through visual inspections and comparative (mesoscopic) assessments of the texture and structure of specimens.

Here, a multi-analytical approach was used to examine ornamental stones used in the 2nd century AD thermal baths of *Teate Marrucinorum* (current Chieti, Abruzzo, Italy). Autoptic, mineralogical, petrographic (textural) and chemical analyses were performed on both white and polychrome lithotypes. A total of 56 rock slabs were first analysed via direct visual inspection and classified according to their mesoscopic features, allowing their categorization into six types: four different polychrome varieties, one grey-striped marble, and a group of white marbles. Then, X-ray powder diffraction (XRPD), micro-Raman spectroscopy, and X-ray fluorescence energy-dispersive spectrometer (XRF-EDS) were used to constrain crystal-chemical features of these rocks and their phases. In addition, isotopic analysis ($\delta^{18}O$, $\delta^{13}C$) was performed on white and grey-striped marbles. Finally, microscopic textural features and structural arrangement of mineral phases (e.g., number, abundance, colour, maximum grain size and boundaries' shape) were evaluated on thin sections with transmission optical microscope (TOM).

The combination of these methods allowed to identify the grey-striped marble from Chieti as Greco Scritto, while it highlighted that the white marbles originated from two sources: Carrara (*Marmor Lunense*) and Marmara Island (*Marmor Proconnesium*). The four polychrome stones were identified as Pavonazzetto antico (*Marmor Phrygium*), Cipollino Verde (*Marmor Carystium*), Portasanta (*Marmor Chium*), and Breccia di Settebasi (*Marmor Scyreticum*). This study emphasises that integrating qualitative inspections with quantitative analyses improves the accuracy of provenance determinations, unveiling more details of the stones used by ancient Romans.

Antonelli F. & Lazzarini L. (2015) - An updated petrographic and isotopic reference database for white marbles used in antiquity. Rendiconti Lincei, 26(4), 399-413, https://doi.org/10.1007/S12210-015-0423-4.

Gnoli R. (1988) - Marmora romana. Edizioni dell'Elefante, 384 pp., EAN:9788871760339.

Provenancing rocks used in ancient Sicilian epigraphy through a multi-analytical approach: data collection, processing and analysis

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Keywords: archaeology, petrography, multi-analytical approach.

A full work package of the interdisciplinary project "Crossreads: Text, materiality, and multiculturalism at the crossroads of the ancient Mediterranean" (https://crossreads.web.ox.ac.uk/) is dedicated to the materials of ancient Sicilian inscriptions, alongside their palaeographic and linguistic aspects, for the study of the epigraphic culture of the island (c. 6000 inscriptions). The precise characterization of stone supports, either available locally or through maritime transport across the Mediterranean (as marble) will provide the first systematic account of the material aspects of this epigraphic culture, and is the first step for further social, economic and cultural considerations.

For the materials characterization, a multi-analytical approach is deployed, including fully non-invasive analyses such as digital microscopy imaging and X-rays fluorescence (pXRF), as well as micro-destructive ones, such as X-rays diffractometry (XRD), minero-petrographic observation of thin sections (OM), and isotopic analyses for marbles.

So far, ca. 700 inscriptions have been subjected to in situ analyses, and ca. 300 to laboratory ones. The variety of rock types and the multitude of different types of information being collected (from numeric values, such as $\delta^{13}C$, $\delta^{18}O$, maximum grain size (MGS), to mineralogical species as % from refinement of XRD patterns, standardized elemental compositions from processing of pXRF spectra, descriptive values inferred from the macroscopic and microscopic appearance) made it necessary to develop some degree of automation in the data processing and management.

A set of digital tools exploiting Colab and Jupiter notebooks written in Python – with associated code repository in evolution at the time of writing (https://github.com/kingsdigitallab/crossreads-petrography) - has been developed to minimize repetitive tasks and human errors, while maintaining control throughout the process.

All the data are currently stored in multiple flat tables, with both samples and references. An image server (IIIF) is being set up for microscopy images, both digital and optical. Simple filtering supports the comparison of rock types, while numeric data can easily be extracted for further analysis, such as chemometrics on the corrected data from pXRF, or data fusion, or the generation of interactive visualization of isotopic values on graphs from the literature.

While the data are currently stored by the project, the resulting interconnected dynamic notebooks are being documented as they evolve and will be released under an open license to make the analysis reproducible but also re-usable by other researchers dealing with similar types of petrographic data collection, processing and analysis.

New data for knapped lithic industry of first farmers at Trasano: chert supply strategies in the framework of Early Neolithic communities of Matera area

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Keywords: Early Neolithic, chert, provenance.

The site of Trasano is located on the eastern side of Matera, along the SS7 to Laterza, at the bottom of the Murgia plateau. Excavations conducted from 1984 to 1991 (Guilane & Cremonesi, 1987), allowed the identification of important traces of frequentation of the area ranging from the earliest phases of the Early Neolithic to the Eneolithic. The occupation of the site during the Early Neolithic can be referred to two ovens, some burials and two stone walls, the larger of which divided the site into two sectors - East and West. In the stratigraphic series of East sector the various stages of evolution of the Impressed Ceramics horizon (Early Neolithic) from an ancient to an advanced phase (end of VII/beginning of VI millennium cal BCE - first half of VI millennium cal BCE) are documented (Radi et al., 2000). In the West sector, on the other hand, the bichromic painted pottery phase (Middle Neolithic) are mainly attested. Numerous silos documented the reoccupation of the site during the Serra d'Alto phase (Middle-Recent Neolithic).

A probabilistic sampling was carried out from the three Early Neolithic stages (Trasano I, Trasano II, Trasano III) of the East sector area B, obtaining 90 chert artifacts (30 samples for each layer) randomly selected. All the samples were investigated by nondestructive petrographic and chemical (pXRF) analyses to understand the provenance of raw materials according to NM-PCI protocol (Delluniversità et al., 2019).

Already the chert knapped lithic industries of Early Neolithic from Giavarra, Murgia Timone, and Trasanello have been analyzed with the same methodology, showing two different chert supply patterns (Muntoni et al., unpublished). At Giavarra the clear prevalence of exogenous chert might instead reflect that neolithic groups that frequented the site were among the first pioneer communities to colonize this area as early as the end of VII millennium cal BCE. At Trasanello and Murgia Timone (first half of VI millennium cal BCE), by contrast, cherts from Gargano formations are clearly subordinate to lithotypes from locally pebbles and this seems to testify to communities that were by then fully integrated into the Matera area.

The three phases of Early Neolithic frequentation attested at Trasano make it a key site for reconstructing the evolution of knapped lithic industries between the end of VII and the first half of the VI millennium cal BCE in the Matera area.

The chert lithotypes identified at Trasano seem to show a substantial balance between the lithologies related to local pebbles and the exogenous cherts related to Gargano promontory formations. These data place Trasano in the same chrono-cultural framework of the close sites of Giavarra and Trasanello (Radi et al., 2000).

This, in relation to the supply of lithic resources, could indicate that as first Neolithic groups became more stably and extensively settled in the Matera area, their increasing knowledge of the area and its resources allowed them to reduce their dependence on exogenous resources.

Guilaine J. & Cremonesi G. (1987) - L'habitat néolitique de Trasano (Matera, Basilicate). Premiers résultats. Atti XXVI Riun. Scient. I.I.P.P: 707-719, Firenze.

Radi G. et al. (2000) - Trasano e la ceramica impressa nel materano. La Neolitizzazione tra Oriente e Occidente Convegno di Studi, Udine aprile 1999: 439-450 Udine, 30.X.2000 Museo Friul. St. Nat. Acc. Ud. Sc. Let. Arti.

Delluniversità E. et al. (2019) - Development of a multiparametric characterisation protocol for chert investigation and application on the Gargano Promontory mines. Archaeological and Anthropological Sciences, 11, 6037-6063.

Muntoni I.-M. et al. (unpublished) - Local and allochthonous chert supplies in three Early Neolithic settlements in the Matera area (Basilicata, Southern Italy). EAA 2024 28-31 Aug Rome, Persisting with change, Poster.

The necropolis of Pontecagnano (Salerno): preliminary diagnostic analyses of impasto ware from the Orientalizing Period (725-575 BC)

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Keywords: impasto ware, Pontecagnano, archaeometry.

Pontecagnano is located in the northern sector of the alluvial-coastal plain of the Sele River, an area characterized by early Pleistocene travertine outcrops. The landscape was shaped by erosional incisions that defined slightly elevated morphological units running longitudinally. The settlement of Pontecagnano occupied one of these units, bordered to the east and west by two necropolises. Since the 1960s, over 10,000 burials dating from the Early Iron Age to the mid-3rd century BCE have been uncovered, providing an exceptional context for the typological and technological analysis of material culture.

During the Early Iron Age, impasto pottery represents the most prevalent ceramic class, characterized by a medium-fine textured fabric, shaped on the potter's wheel, with a smoothed and polished surface, typically brown. A preliminary typological sequence—based on a limited corpus—was proposed by B. D'Agostino (1968), who already noted the challenges in distinguishing between local and imported wares Subsequent systematic analyses of the necropolises have significantly expanded the dataset, elucidating the complexities and developments of both local production and imports from various regional contexts, including the Etruscan and Italic spheres.

In this framework, a series of investigations started to examine the production technologies by mineralogical and petrographic analyses aimed to define the characteristics of local manufacturing, and eventually identify the occurrence of imported ceramic productions.

An initial analytical step was conducted on a set of 130 samples investigated by digital microscopy (DM), attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR), and fiber-optic reflectance spectroscopy (FORS). Data acquired from the preliminary analytical step also permitted the reduction of the number of samples (36 samples) to be powdered and thin-sectioned for further investigation, including thermogravimetric analysis (TGA), mineralogical-petrographic analysis in thin section (PLM), and powder X-ray diffraction (XRPD). Preliminary, the ceramic findings revealed notable heterogeneity in the ceramic pastes, ranging from medium to coarse-grained with volcanic to siliciclastic inclusions, to fine-grained. Colorimetric measurements and mineralogical analyses confirmed that the firing processes were not always well-controlled.

D'Agostino B. (1968) - Pontecagnano. Tombe Orientalizzanti in contrada S. Antonio, in Notizie di Scavo 1968, 75-194.

Provenance of Euganean building materials: 10 years of collaborative archaeometric research at the University of Padova

Dilaria S.[1-2], Germinario L.*[3], Bonetto J.[1], Girotto C.[1], Maritan L.[3], Olah J.[1], Previato C.[1], Sassi R.[3], Secco M.[1-2], Zara A.[1] & Mazzoli C.[3]

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Keywords: provenance study, volcanic rock, volcanic pozzolan.

The Euganean Hills, located a few km from Padova, represent one of the most important historical quarry districts of northeastern Italy. They are renowned for the extraction of trachyte, with the earliest evidence dating to prehistoric times and a large-scale exploitation beginning during the Roman period. This natural resource has been widely utilized as building stone in public and private construction and monuments, as carving stone for crafting diverse artifacts, and even as temper in pottery production. Among the lesser-known Euganean materials historically used on a smaller scale are rhyolites and, most notably, volcanic breccias; the latter were primarily employed as reactive aggregate in mortars and concrete, an ancient use that remained undocumented until recently.

The presence of numerous Euganean quarries complicates provenance studies of archaeological materials, which can shed light on ancient trades, quarrying activities, stone selection, and territorial organization and influence of settlements. These questions have been addressed in the last years by our multidisciplinary team of geologists, archaeologists, and heritage scientists of the University of Padova (Maritan et al., 2013; Germinario et al., 2018a, 2018b; Dilaria et al., 2024), marking a significant step forward from previous archaeometric research, began as early as thirty years ago.

This contribution delivers an overview of our recent collaborative studies aimed at identifying and applying a set of tracers for discriminating Euganean quarries and recognizing the provenance of natural and artificial geomaterials (stones, mortar, concretes) in archaeological contexts. Our first efforts were concentrated in the creation of a reference database for high-resolution provenance studies of trachyte. The provenance criteria proposed encompass a range of petrographic and geochemical markers related to the mineralogical composition, textural features of phenocrysts and groundmass, major- and trace-element composition of the bulk rock and phenocrysts. The analytical approach was multidirectional, based on optical microscopy, SEM-EDS, μ-XRF, XRF, LA-ICPMS, image analysis, and a robust statistical multivariate data analysis. Subsequent research was aimed at testing the provenance tracers on archaeological materials from different Roman archaeological sites in Veneto region; at the same time, complementary approaches including QPA-XRPD analyses and semi-automated machine learning tools for provenance attribution based on multivariate statistics were introduced. Finally, new surveys with drone and LiDAR technologies, within a project currently in implementation, are allowing mapping and documenting new quarry sites that had been neglected and overgrown with vegetation. Our field investigations confirmed clear evidence of widespread ancient extraction activities, and a new set of samples was recently collected to update the geological reference for potential source materials.

Dilaria S. et al. (2024) - The stone artifacts of the National Archaeological Museum of Adria (Rovigo, Italy): a noteworthy example of heterogeneity. Archaeological and Anthropological Sciences, 16, 14, https://doi.org/10.1007/s12520-023-01911-4.

Germinario L. et al. (2018a) - New petrographic and geochemical tracers for recognizing the provenance quarry of trachyte of the Euganean Hills, northeastern Italy. Geoarchaeology, 33, 430-452, https://doi.org/10.1002/gea.21666.

Germinario L. et al. (2018b) - Tracking trachyte on the Roman routes: provenance study of Roman infrastructure and insights into ancient trades in northern Italy. Geoarchaeology, 33, 417-429, https://doi.org/10.1002/gea.21667.

Maritan L. et al. (2013) - Trachyte from the Roman aqueducts of Padua and Este (north-east Italy): a provenance study based on petrography, chemistry and magnetic susceptibility. European Journal of Mineralogy, 25, 415-427, https://doi.org/10.1127/0935-1221/2013/0025-2282.

Toward a standardized GIS-based lithotheque: The OPENLIT Project and the Italian chert resources

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Keywords: chert, GIS, lithology.

In line with efforts by various European countries attempting to create geo-referenced lithoteques designed for the characterization of lithic resources, the OPENLIT project aims to create the first Italian open-access lithoteque, a reference collection of knappable rocks based on a multi-parametric GIS-based database. The aim is to develop a standardardized analytical and descriptive system for defining knappable rocks based on laboratory testing and make it available to the scientific community through an open- access repository.

Priority has been given to chert, due to its key role as raw material in prehistory and to the need to provide a sound geological and petrological framework for accurate lithological classification and correlation with lithic artifacts.

In this contribution, we present the architecture of the geo-referenced database, along with the strategy to obtain interactive GIS-based chert resource maps and relative analytical data (petrography, micropaleontology, pXRF, surface features) and references. Two case studies are illustrated and discussed as examples of data input and extraction from the database.

The project will provide an open and implementable research tool that integrates different methodologies and establishes reference groups for comparisons with prehistoric collections.

Comparing lithic industry and psephitic sediments of Notarchirico (Basilicata, Italy): new data to understand human-environment interaction and technological behavior during the Lower Paleolithic in Southern Europe (MIS 16-15)

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Keywords: lithic industry, lithology, Paleolithic.

The site of Notarchirico (Basilicata, southern Italy) represents a significant context for understanding technological behavior and human-environment interaction in Western Europe during the Middle Pleistocene. In the stratigraphic sequence, including more than 10 human occupation phases between 700 and 600 ka, archaeological artifacts and faunal remains, currently housed at the Castello di Venosa, were collected. They allow describing Lower Paleolithic occupations including for some, Acheulean with bifaces. The bifaces are among the oldest artifacts in Western Europe. This study, belonging to the interdisciplinary program ERC LATEUROPE, focuses on the petrographic characterization and dimensional analysis of more than 1,000 artifacts found in 6 levels (E-F, F, G, H, I1 and I2) dated between 670 and 695 ka. This study aims to contribute to the investigation of the modes of raw materials collecting by hominin groups, if they selected (1) only local stones found in situ and/or (2) some specific materials depending on the categories of tools. Each sample was classified according to lithology, structure, texture, and lithotype, by means of a stereomicroscope. Results indicated an assemblage generally dominated by chert (radiolarites and silicified calcirudites, calcarenites and calcilutites) and limestone (mudstone, wackestone, packstone and rudstone), with additional occurrences of marl and sandstone, even if some values difference were highlighted in each level. In order to enhance the knowledge on raw material procurement strategies, the archaeological artifacts were compared with geological pebbles and cobbles embedded in level B. As dense and minimally anthropized paleosurface, this level serves as a representative proxy for the geolithological landscape of the fluvio-lacustrine environment available to hominins at the time. In addition, the archaeological materials were compared with reference samples from the SiLiBA lithotheque, housed at the Earth and Geoenvironmental Sciences departments of the University of Bari Aldo Moro (Italy), which includes geological Formations from the outer tectonic units of the Southern Apennines chain. Preliminary analytical data and comparative framework results suggested a deliberate selection of high-quality rocks for knapping and a preferential use of local resources, though evidence of non-local material allowed to introduce patterns of landscape use and mobility. These findings contribute to the understanding of the technological strategies employed by Lower Paleolithic hominins in southern Italy and to deep their technological and behavioral complexity.

Tracing origins: mineralogical and petrographic insights into Archaic and Classical roof tiles from Castro (Lecce)

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Keywords: Apulian terracotta, raw materials provenance, technological features.

Since the year 2000, systematic archeological excavations have uncovered the ancient sanctuary of Athena at the indigenous site of Castro (Lecce) on the Adriatic coast of ancient Messapia (southern Apulia, Italy). Between the 7th and 2nd centuries BCE, this site served as a meeting place for local populations, Greek settlers from Taranto and people from Macedonia, Epirus and the Corinthian colonies along the Adriatic. From the late 6th century BCE, temples and other religious buildings were erected and decorated with brightly colored terracotta roofs. Several different roof styles have been identified on the basis of morphological and stylistic analyzes. Many of these roof styles have been attributed to workshops in Taranto, although some styles could not be assigned due to their ambiguous characteristics (D'Andria et al., 2023). In order to determine the type of raw material and its origin, several sampling campaigns were carried out. Twenty representative samples from Archaic and Classical roof types were analyzed in detail via Polarized Optical Microscopy (POM), Quantitative X-ray Powder Diffraction (Q-XRPD) with the Rietveld method, X-ray Fluorescence (XRF) and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS). Based on the petrographic and mineralogical data, we can divide the samples into four groups, each characterized by a different amount of volcanic and carbonate inclusions and different properties of the clay matrix. The firing temperature of each sample was determined by its mineralogical composition, the optical activity of the clay matrix and the degree of sintering. EDS microanalysis of minerals such as clinopyroxenes, feldspars and volcanic glass suggests that the aplastic inclusions are probably comparable to some pyroclastic deposits from the island of Ischia (D'Antonio et al., 2021). Chemical and mineralogical comparisons between our terracotta samples and clay raw materials occurring in the Taranto and Castro areas showed a reasonable geochemical similarity with the clay sediments of Taranto. These findings provided new insights into the sources and transportation of raw materials as well as the technical skills of the Taranto craftsmen.

D'Andria F. et al. (2023) - Athenaion: Tarantini, Messapi e altri nel santuario di Atena a Castro. Catalogo della mostra, MArTA - Museo archeologico nazionale di Taranto, MAR di Castro - Museo archeologico "Antonio Lazzari" di Castro, Bari.

D'Antonio M. et al. (2021) - Petrography and mineral chemistry of Monte Epomeo Green Tuff, Ischia Island, South Italy: Constraints for identification of the Y-7 tephrostratigraphic marker in distal sequences of the Central Mediterranean. Minerals, 11, 955, https://doi.org/10.3390/min11090955.

Minero-petrographic and geochemical characterization of Brecce di Seravezza (including Medici's Breccia), Apuan Alps (Italy)

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Keywords: Breccia di Seravezza, geo-mineralogical characterization, cultural heritage.

The Brecce di Seravezza s.l. (including Medici's Breccia) represent a geological and commercial peculiarity in the heritage of the Apuan Alps (Tuscany, Italy). The appearance of this ornamental stone varies, due to the size and the color of the clasts and matrix, of provenance from one quarry to another and within the same quarry depending on its stratigraphic level, giving rise to different commercial types and varieties.

In this contribution, samples coming from two historical quarries of the typical Stazzema area (Cava del Rondone c/o Ponte Stazzemese and Grotte Bianche c/o Volegno) were fully characterized through petrographic, mineralogical and micro-chemical analyses. The Breccias of these two geological sections are stratigraphically interposed between the Marmi a Megalodontidi (massive or coarsely stratified white to light grey marbles that include small lenticular dark grey areas), at the bottom, and Marmi (grey "Bardiglio" marble with local dolomitic marble interbeds), at the top. The "classical" feature of the Brecce di Seravezza s.l. used in art and architecture (consisting in a "disorganized" breccia with whitish to reddish marble and minor dolomitic marble pebbles to boulders in a reddish/violet, foliated carbonatic-phyllitic matrix) is recognizable only in some parts of the geological sections.

Petrographic and microstructural observations in polarized light (PLM), mineralogical qualitative analyses with X-ray powder diffraction (XRPD), Scanning Electron Microscope Energy-Dispersive Spectroscopy (SEM-EDS) analyses allow us to identify the main features for 14 representative samples (8 from Cava del Rondone section and 6 from Grotte Bianche section).

Furthermore, the main uses of these materials in the cultural heritage context and the main decay phenomena observed in the outdoor and indoor will presented.

Brilliant blue and hidden practices: scientific insights into the polychromy of a *sacrarium* in the *Insula 10*, *Regio IX*, Pompeii

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Keywords: Egyptian Blue, pigments, spectroscopic techniques.

Pompeii, owing to its exceptional state of preservation, constitutes an unparalleled context for reconstructing the techniques and daily practices of ancient Roman life, enabling detailed investigation into their domestic, cultic, and artistic activities. Within this framework, recent investigations in the *Insula* 10 of *Regio* IX at Pompeii have brought to light a room identified as a *sacrarium*, decorated with Fourth Style wall paintings and distinguished by an intense blue pigment extending across the walls.

Originally conceived as a space for private religious worship, the *sacrarium* was repurposed as a storage area shortly before the 79 CE eruption. Stratigraphic analyses have documented its subsequent use for storing amphorae and construction materials, with clear evidence of ready-to-use *cocciopesto* and *pozzolana* deposits. Moreover, an accumulation of oyster shells discovered near the threshold of the *sacrarium* also suggests their post-consumption reuse.

The wall decoration features iconographic motifs including personifications of the Seasons—an established theme in Pompeian painting—alongside female figures and scenes evocative of rural symbolism. The vivid blue used to decorate the walls constitutes a rare and elaborate example of Pompeian decoration, generally used to adorn rooms with highly elaborated decorations; it completed the compositional scheme with allegorical representations linked to agricultural themes.

The polychromy of both the *sacrarium* and the adjoining *vestibulum* was investigated in situ using a multi-analytical non-invasive approach combining microscopy and spectroscopy. Digital Microscopy (DM), Fiber Optics Reflectance Spectroscopy (FORS) in the visible range, portable X-Ray Fluorescence (pXRF), Fourier Transform Infrared Spectroscopy (FTIR) in Attenuated Total Reflectance (ATR) mode, and Raman Spectroscopy (RS) were employed to characterize the pigments. The analyses identified complex pigment mixtures comprising inorganic compounds (Egyptian blue, calcite, red and yellow ochre, red lead, green earth, orpiment) as well as organic components (carbon black), deliberately blended to achieve specific hues and chromatic effects.

In addition, two samples—a painted plaster and a stucco fragment—were subjected to laboratory-based investigations to better understand the application techniques and constituent materials. Microscopic analyses, including Polarized Light Microscopy (PLM) and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS), revealed a multi-layered plastering technique. The lime-based mortar incorporated a carbonate aggregate in the *intonachino* layer, on which the blue pigment was applied.

Notably, detailed analysis through synchrotron radiation micro X-ray diffraction (SR-μXRD, Tortosa et al., 2027) were performed, revealing a complex stratigraphy and a specific choice of raw materials to create each layer.

Tortos A. et al. (2027) - Structural analysis of historical materials [Dataset]. European Synchrotron Radiation Facility, https://doi.org/10.15151/ESRF-ES-1940867633.

Multi-analytical approach for estimating the provenance of lithic material from the prehistoric site of Pirro Nord (Apricena, southern Italy)

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Keywords: lithic tools, chert, provenance.

Pirro Nord, situated in Apricena (Puglia, Southern Italy), is a prehistoric site dated between 1.6 and 1.3 million years ago. It presents the earliest known evidence of hominin presence on the Italian peninsula. Fossil remains (Pirro Nord Faunal Unit) and lithic industries were found within a Pleistocene paleokarst formation that overlies Mesozoic limestone inside a quarry used for extracting Apricena Stone (Arzarello & Peretto, 2010).

Archaeological evidence indicates that raw materials were likely collected from secondary deposits, possibly associated with riverbeds. However, the procurement strategies and distances remain unknown, and scientific data have not yet supported the opportunistic behaviour hypothesized in lithotype selection.

This research aims to identify potential raw material procurement areas through the analysis and comparison of mineralogical, textural, and compositional features of archaeological and geological samples. To achieve this goal, a multi-analytical approach was adopted, combining non-invasive spectroscopic, mineralogical, and geochemical techniques, to pre-select a subset of samples for more detailed invasive analyses.

This study presents the results obtained from 71 archaeological knapped samples, 63 archaeological non-knapped samples, and the samples from 1 secondary deposit and 9 primary deposits. Preliminary investigations were carried out on all samples using non-invasive techniques, including Digital Microscopy (DM), Fourier Transform Infrared Spectroscopy (FTIR) using an External Reflectance module (ER-FTIR), Fiber Optical Reflectance Spectroscopy (FORS), and portable X-Ray Fluorescence (pXRF) that provided relevant information for further investigation (Lepore et al., 2024).

Based on the outcomes of these non-invasive analyses, a selection of representative non-knapped archaeological materials and geological materials was prepared as thin sections and examined using polarized light microscopy (PLM).

Three main lithotypes were identified: i) chert composed solely of microcrystalline quartz, occasionally containing oxides; ii) chert composed of microcrystalline quartz with silicified fossil remains, silica microspheres, and oxides; iii) silicified calcarenites in which both clasts and cement are partially or fully replaced by silica and fibrous chalcedony. Similar textural and mineralogical characteristics were observed in geological samples collected from a secondary deposit located approximately 1 km from the Pirro site. These hominins may have exploited polygenic pebbles from this nearby deposit as raw material sources. However, certain lithotypes identified among the archaeological samples were not found within this deposit, indicating the likely presence of multiple, yet unidentified, raw material sources.

Arzarello M. & Peretto C. (2010) - Out of Africa: The first evidence of Italian peninsula occupation. Quaternary International, 223-224, 65-70, https://doi.org/10.1016/j.quaint.2010.01.006, https://doi.org/10.1007/s12520-019-00875-8.

Lepore A. et al. (2024) - Multi-analytical study of lithic materials from the prehistorical site of Pirro Nord: preliminary results. In: Joint Congress of Società Geologica Italiana (SGI) and Società Italiana di Mineralogia e Petrologia (SIMP) "Geology for a sustainable management of our Planet", Bari.

Traces of colour/paint on the rock-reliefs of the Assyrian irrigation system at Faida and Khinis (Iraqi Kurdistan)

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Keywords: microstructure, limewash, fresco technique.

The impressive water-management system built in the eighth-seventh century BC by the Assyrian king Sennacherib in the hinterland of Nineveh, on the left bank of the Tigris river in Mesopotamia (Iraqi Kurdistan), consists of a network of hundreds of kilometres of artificial channels created for irrigating the plain of the ancient capital of the Assyrian Empire (Morandi Bonacossi, 2018). This irrigation network testifies to the enormous power of the king which is celebrated, at the head of the channel system and along its course, by commemorative monumental rock-reliefs carved on the Eocene dolostone constituting the bedrock of the area.

During the extensive cleaning and restoration of these reliefs, carried out within the Land of Nineveh Archaeological Project (LoNAP) in the archaeological sites of Khinis and Faida, numerous micro-samples were collected to analyse the reliefs' surfaces that in some points were very compact and smoothed, and brown-reddish, suggesting the possible presence of an applied coating. The analysis at the stereomicroscope and especially that at the scanning electron microscope indicated that the samples from the reliefs are composed of two different portions, since the dolomitic rock on which the reliefs were carved was covered by a very fine-grained calcite layer, corresponding to a limewash. The high-resolution micro-stratigraphic analysis indicated that this limewash is composed of numerous layers, each with a thickness of a few micrometres, often showing a carbonation surface (marked by a denser material), indicating that between the application of one layer and the subsequent one, at least a few hours passed. Moreover, in the most external layer of the limewash, traces of red earth are also preserved, used to colour the reliefs' surface in red. Samples of the bedrock, collected near the reliefs, show the absence of calcite deposits on the surface of the dolostone.

Both the reliefs of Khinis, continuously exposed to weathering throughout the centuries since their creation, and those of Faida, covered by the passive infilling of the channel by sediments after its abandonment after the collapse of the Assyrian Empire in 612 BC, preserved fragments of the limewash, documenting for the first time traces of fresco and painting on Assyrian rock-reliefs and its application technique.

Morandi Bonacossi D. (2018) - Water for Nineveh. The Nineveh Irrigation System in the Regional Context of the 'Assyrian Triangle': A First Geoarchaeological Assessment", in H. Kühne (ed.), Water for Assyria, Studia Chaburensia 7. Harrassowitz: Wiesbaden, 77-115.

Reconstructing manufacturing and corrosion processes of a trimetallic Etruscan artefact from Pyrgi (Santa Severa, Italy)

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Keywords: trimetallic artefact, Etruscan metallurgy, galvanic corrosion.

This study examines a complex trimetallic artefact composed of three concentric layers, *i.e.*, an iron core, an intermediate lead shell and an outer bronze shell, from the archaeological site of Pyrgi (Santa Severa, Rome), dating back to the 5th-4th centuries BCE. The aim is to reconstruct both the manufacturing process and the degradation pathway of the artefact, evaluating the extent to which the original production choices and the post-depositional burial conditions influenced its corrosion. A combination of optical microscopy (OM), scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS), and micro-Raman spectroscopy (μ-RS) was employed. The results indicate that the iron core was hot-forged, while the outer high-tin bronze shell displays a cast microstructure subjected to thermal treatments, such as quenching from high temperatures (Park et al., 2009). Evidence of lead infiltrating the recesses of the bronze shell supports the following interpretation, *i.e.,* the manufacturing sequence includes a) the forging of the iron core, b) the shaping of the high-tin bronze cylindrical shell, c) the core insertion, and d) the final casting of molten lead to fill the interstitial space. The corrosion model highlights galvanic coupling as the primary degradation mechanism (Ng et al., 2020), increased by the marine burial environment. This led to the complete dissolution of the metallic iron in the core, replaced by goethite (α-FeO(OH)) and magnetite (Fe_3O_4), and to the formation of laurionite (PbCl(OH)) at the iron-lead interface (Trueman et al., 2017). Additionally, the occurrence of hydrocerussite ($Pb_3(CO_3)_2(OH)_2$), cuprite (Cu_2O), and copper trihydroxychlorides ($Cu_2Cl(OH)_3$) at the lead-bronze interface involved the mechanical detachment of the bronze shell.

Ng D.Q. et al. (2020) - Lead release in drinking water resulting from galvanic corrosion in three-metal systems consisting of lead, copper and stainless steel. Journal of Hazardous Materials, 398, 122936, https://doi.org/10.1016/j.jhazmat.2020.122936.

Park J.S. et al. (2009) - Implication of peritectic composition in historical high-tin bronze metallurgy. Materials Characterisation, 60, 1268-1275, https://doi.org/10.1016/j.matchar.2009.05.009.

Trueman B.F. et al. (2017) - Galvanic corrosion of lead by iron (oxyhydr)oxides: potential impacts on drinking water quality. Environ. Sci. Technol., 51, 6812-6820, https://doi.org/10.1021/acs.est.7b01671.

Determining the provenance of stones from southern Italy with AI and geochemical data

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Keywords: stones identification, provenance, neural networks.

This study presents a novel methodological framework for determining the provenance of stones sourced from ancient Calabrian quarries (Southern Italy), integrating both multivariate statistical analysis and artificial intelligence (AI). A total of twenty-five quarries (De Luca et al., 2021) located throughout the provinces of Calabria were sampled, with ten samples taken from each quarry, resulting in an overall total of 250 samples. These samples were analysed using polarized light microscopy, X-ray powder diffraction (XRPD), and X-ray fluorescence (XRF), focusing specifically on their geochemical composition.

The geochemical dataset, comprising major and trace elements, was used to build discriminant models employing Linear Discriminant Analysis (LDA) and Principal Component Analysis (PCA). These models demonstrated strong efficacy in distinguishing between lithotypes, particularly when applied to calcarenites, biocalcarenites, igneous and metamorphic rocks. However, certain calcium carbonate-rich stones posed challenges for classification due to overlapping compositional signatures.

To address this, a complementary approach using machine learning was adopted. A neural network was developed and trained using TensorFlow/Keras within a custom-built Python-based software named "PetroChem AI 1.0". The training dataset included both real and synthetically generated geochemical data, the latter obtained by applying Gaussian noise to preserve the statistical integrity of each rock type. The resulting neural network achieved an overall accuracy of 93.44% during validation, but it showed limitations in correctly classifying rocks with high calcium carbonate content, such as the "Calcarenite di Crotone" and "Calcare di Grisolia".

To improve usability for non-specialist users such as archaeologists and conservators, the trained model was embedded in a stand-alone executable (Classifier.exe) with a user-friendly interface that allows rock classification based solely on major element compositions.

By making both the geochemical database and the AI tools free available, this work fills a significant gap in the archaeometric study of Calabrian stone materials and lays the groundwork for future improvements, such as the development of specialized neural networks focused exclusively on carbonate rocks using integrated datasets of major and trace elements.

De Luca R. et al. (2021) - RecoStones: A new tool to identify Calabrian stone materials through image processing. Geoheritage, 13 (41), https://doi.org/10.1007/s12371-021-00564-w.

Provenance and production technology of the painted architectural terracottas from the Northern Sanctuary of Cuma (Campania region, Southern Italy)

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Keywords: architectural terracotta, Cuma.

Archaeological research by the Centre Jean Bérard near the northern fortifications of ancient Cuma has brought to light a sacred area with evidence of continuous activity from the 6th to 4th centuries BCE. Excavations revealed votive pits, likely associated with formal rituals marking the closure and abandonment of the site, containing painted architectural terracottas from two distinct chronological phases dated to the Archaic and Hellenistic age. The presence of materials from both phases reflects an intentional effort to conserve elements of sacred structures over time, preserving the memory of the full life cycle of the sanctuary (Munzi, 2014). Although the selected materials show a clear typological evolution, this study investigates whether these morphological changes were accompanied by variations in technological practices, with the aim of identifying potential developments over time. A multi-analytical approach was adopted to study eighteen samples, to investigate the composition and provenance of raw materials, the production techniques and firing technologies.

Textural, mineralogical and compositional analyses did not reveal significant differences between the two chronological phases. Polarized Light Microscopy (PLM) of thin-section showed that, in both phases, most samples are featured by a coarse fabric with volcanic temper scattered in the clayey matrix. The temper is composed of scoriae, pumices, feldspars, clinopyroxene and biotite, mineralogically consistent with Phlegraean volcanic products, suggesting a local production. X-ray Fluorescence (XRF) analyses confirmed the use of high-CaO clays (6–10 wt.%) across all samples. The chemical dataset, processed with Principal Component Analysis (PCA), showed compositional affinities with clays from Ischia island, one of the main clay sources in the Gulf of Naples. X-ray powder diffraction (XRPD) data, instead, shed light on the production technology. A limited set of samples, characterised by the presence of calcite and illite/mica, likely did not achieve firing temperatures of 850 °C, while a more substantial group, distinguished by the presence of newly formed minerals (gehlenite and/or diopside) experienced higher firing temperatures, occasionally exceeding 950 °C.

Surface decorations were investigated via Fiber Optic Reflectance Spectroscopy (FORS) in Vis-range, Fourier Transform Infrared (FTIR), XRF and μ-Raman spectroscopy. Three primary colours were identified: white, black, and various shades of red to brown. Red surfaces were consistently associated with hematite, while black decorations involved iron-based pigments such as magnetite or hematite, often combined with manganese compounds. In these latter cases, pigments may have been applied before the firing, supporting the hypothesis of different firing conditions. Furthermore, a thin preparatory wash, likely composed of diluted clay and lime, was frequently observed as a coating layer to protect the clay surface.

Munzi P. (2014) - Il Santuario periurbano settentrionale di Cuma. In: Rescigno C., Sirano F. (Eds), Immaginando città. Racconti di fondazioni mitiche, forma e funzioni delle città campane. Santa Maria Capua Vetere – Paestum, 140-143.

Inclusions and microstructures revealing technological signatures in copper alloys artefacts from the Etruscan site of Pyrgi (Latium, Italy)

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Keywords: tellurium-selenium inclusions, lead-bismuth, Etruscan smelting processes.

The Etruscan site of Pyrgi (Santa Severa, Italy), an ancient port of Caere, has yielded metal artifacts that offer insights into the metallurgical practices. The study focuses on a selection of copper-based nails and *aes rude* (proto-money), investigating their microstructure, alloy composition, and the nature of inclusions to infer technological choices and provenance of the raw material. The artifacts were analyzed using SEM-EDS, with special attention to metallic and nonmetallic inclusions, indicative of ores deposits and processing procedures.

Nails and *aes rude* generally show an almost pure copper matrix, with low concentrations of tin and lead. Inclusions of Pb-Bi, Pb-Te, Cu-S-Te and S-Fe were found consistent with the use of polymetallic sulfide minerals (Cadet et al., 2019). Tellurium and selenium are often associated with hydrothermal systems and volcanogenic massive sulfide deposits (VMS). In the artifacts analyzed, these elements were identified in the nails but were absent in most of the *aes rude* (Cano et al., 2025). This disparity suggests different smelting sources or practices. Se and Te are lost at high-temperature processes due to their volatility, but their presence in artifacts are indicative of low-efficiency refining techniques or incomplete roasting of sulfide ores (Wang et al., 2018; Makuei et al., 2018). This leaves microinclusions that serve as geochemical fingerprints of the original mineral source. These residual elements offer valuable clues about the degree of purification achieved by Etruscan metallurgists and technological limitations or intentions in metalworking. The variability of inclusion composition is related to the nature of the ore deposit but also to choices in ore selection and metallurgical refining strategies.

These findings help reconstruct resource supply, smelting process, and alloy production at Pyrgi (Central Italy) during the first millennium B.C., expanding acknowledgments of how Etruscan societies managed raw materials and metallurgical processes.

Cadet M. et al. (2019) - Laos' central role in Southeast Asian copper exchange networks: A multi-method study of bronzes from the Vilabouly Complex. J. Archaeol. Sci., 109, 104988, https://doi.org/10.1016/j.jas.2019.104988.

Cano N. et al. (2025) - Transient non-soluble noble metal transport in hydrothermal ore systems. Nature Commun., 16, 2521, https://doi.org/10.1038/s41467-025-57740-7.

Makuei F.M. & Senanayake G. (2018) - Extraction of tellurium from lead and copper bearing feed materials and interim metallurgical products – A short review. Minerals Eng., 115, 79-87, https://doi.org/10.1016/j.mineng.2017.10.013.

Wang Q. et al. (2018) - Copper ingots from a probable Bronze Age shipwreck off the coast of Salcombe, Devon: Composition and microstructure. J. Archaeol. Sci., 97, 102-117.

Towards raw material provenance: protocols and perspectives for studying of Roman painted plasters in Northern Etruria

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Keywords: archaeometric analysis, pigment provenance, Roman painted plasters.

Painted plasters represent one of the most extensively investigated materials in cultural heritage studies, examined from a range of disciplinary perspectives. Initial research primarily focused on decorative aspects; however, from the second half of the twentieth century onwards, archaeometric approaches have enabled a deeper understanding of their material composition and manufacturing processes. In recent years, the development and adoption of portable, often non-invasive, instrumentation have significantly expanded the potential for investigation, allowing for in situ analyses and minimising sampling.

This contribution presents an ongoing research project aimed at characterising the pigments used in painted plasters from archaeological contexts across both the coastal and insular areas of central-northern Etruria. The goal is to reconstruct the ancient chaîne opératoire, from raw material selection through to processing and application, through an integrated, multi-analytic methodology.

The initial phase of the research involves a diagnostic screening of the materials using non-destructive and portable techniques, including digital microscopy, hyperspectral imaging, Raman, ATR-FTIR (Attenuated Total Reflection Fourier Transform Infrared), FORS (Fiber Optics Reflectance Spectra), and XRF (X-Ray Fluorescence) spectroscopy. Widely applied in the study of painted plasters (Cucci et al., 2020; Grifa et al., 2025), these methods enabled the identification of the pigments and mixtures employed, as well as insights into the technical choices made by ancient craftsmen. Moreover, multivariate statistical analyses, specifically Principal Component Analysis (PCA) and Cluster Analysis, were conducted to highlight shared features among the samples and to detect potential outliers, to improve the data exploration and minimise the risk of overlooking significant patterns.

The second phase, still forthcoming, will focus on the provenance of raw materials. A sampling strategy has been established, involving the use of destructive techniques on a limited selection of representative samples, with the aim of identifying geochemical and petrographic markers suitable for comparison with reference materials. Once potential source areas have been hypothesised, local and regional geological surveys will be conducted to validate these assumptions regarding ancient procurement strategies.

This study not only contributes to the reconstruction of ancient production dynamics and supply networks but also serves as a platform to reflect on the efficacy and limitations of current analytical methods. Moreover, it proposes a replicable workflow that can be applied to similar contexts, fostering interdisciplinary dialogue on best practices in the scientific study of ancient pigments.

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Geomaterials as ancient time markers: the evolution of the technological skills in the potteries of the Kazreti Ortvala Cave archaeological site (South Caucasus, Georgia)

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Keywords: archaeometry, Caucasus, ceramics.

The Kazreti Ortvala Cave, located in the Mashavera River valley in southern Georgia (South Caucasus), constitutes a geologically significant volcanic conduit dated back to Pleistocene activity (2.20–2.05 Ma) of the Dzhavakheti volcanic highland producing Mashavera basaltic Flows (Lebedev et al., 2007). Its favourable topography, proximity to river and abundance of natural resources—including rich clay deposits—made it an attractive location for human occupation beginning as early as the prehistoric period. From that time onward, the site appears to have been continuously or recurrently used by human communities until the late medieval period. This sustained occupation has resulted in the preservation of stratified archaeological layers and distinct cultural assemblages, representing multiple chronological phases (Berikashvili, 2024). The ceramic assemblage recovered from the Ortvala Cave spans a broad chronological range and can be divided into three principal groups. The earliest group belongs to the so-called Ceramic Neolithic period of the South Caucasus (ca. 6000–5000 BCE). The vessels lack elaborate ornamentation, refined shapes, or painted decoration. The second group consists of pottery fragments dating to the Bronze Age (ca. 4000–2000 BCE). These differ significantly from the earlier ceramics in terms of manufacturing techniques and quality. Produced on a pottery wheel and fired in kilns, they are more durable and display refined shapes. The third group comprises medieval ceramics, specifically from the 12th–13th centuries CE. These vessels are distinguished by their high technical quality, glazed surfaces, and artistic decoration, and they reflect the material culture associated with the developed-high medieval period in Georgia. The human activity at the site drastically declined in the late medieval period because of a devastating earthquake, until renewed use in the 16th–17th centuries. In this work, 21 samples of potteries have been selected and analysed. They are both glazed and non-glazed ceramics and date back to the three different periods. The research aims to define the technological production processes and highlight any changes over time in terms of raw materials or manufacturing methods. For this reason, the samples have undergone complementary archaeometric analyses. Both ceramic body and glaze, where present, have been investigated. Polarising optical microscope (POM) has provided textural and petrographic features describing the samples according to Whitbread classification (1995); the X-ray diffraction (XRD) determined mineralogical composition with relative firing temperatures information; scanning electron microscopy (SEM) coupled with EDS microanalysis provided data on the morphological aspect of the microstructure (e.g. vetrification degree of the groundmass) and chemical composition in terms of major elements.

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White marbles and coloured ornamental stones from the Roman *nymphaeum* of the Valle Gianni archaeological site (Gradoli, Viterbo)

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Keywords: white marbles, ornamental stones, Valle Gianni.

The excavations of the archaeological site of Valle Gianni (Gradoli, Viterbo), started in 2019, as a part of the project "Northwest Bolsena Archaeological Project" of Illinois State University. This site is located on a hill overlooking the northwestern shore of the Bolsena Lake and consists of partially exposed remains of a Roman imperial period monumental fountain, possibly a *nymphaeum*, and an agricultural area containing a large, recessed vat that predates the fountain but that was eventually replaced by a Late Antique structure. From geological point of view, the area of the excavations is located on a volcanic terrain, mainly the pyroclastic products (tufa) of the late-stage Latera caldera-forming eruptions (Quaternary Vulsini Volcanic Complex).

During the 2023 season, while exploring the area immediately to the west of the fountain, traces indicating an architectural collapse were detected, and at least three related deposit layers. Beneath these layers of collapse, a large deposit of various types and cuts of marble were uncovered. Over one thousand fragments of « marble » were documented, removed, cleaned, and assembled for required storage with the agreement of the Archaeological Superintendency of Southern Etruria. Some fragments of « marble » are thinly sawn and smooth, some show inscriptions, some are thick and carved as cornice molding, some others caked with plaster with revetment pins still attached. All of them look like stone architectural elements and therefore a detailed mineralogic, petrographic and geochemical study was planned.

First of all, among the ornamental lithologies, we separated macroscopically, the marbles *s.s.* (crystalline metamorphic stones) from the igneous and sedimentary rocks. Among the marbles *s.s.* the majority are white and in minor amount grey and green. A large variability of colours were instead emphasized by the sedimentary stones which comprise red and dark fossiliferous limestones and whitish to pinkish limestones whose macroscopic structures closely match with several lithotypes used in antiquity, especially in the Roman Period.

Thin section petrographic study under the polarized light microscope, for the representative groups of white marbles *s.s.* (mainly to determine the Maximum Grain Size and eventually detect accessory minerals), were performed for thirty, together with carbon and oxygen stable isotopes δC13 and δO18).

Our primary goal is to classify the different types of ornamental stones and, if possible, their provenance areas (or reuse as *spolia*) making some inferences about the time of construction and the original decorative schema on the fountain. Another aim of the study will be tracing the main terrestrial and/or water-ways routes and commercial networks allowing precious «marbles» to reach Valle Gianni which is outside the Cassia Consular Road joining Rome to Etruria, running along the eastern sectors of the Bolsena Lake.

Petrographic characterization of re-used stone materials in medieval contexts in Cisalpine area (Piemonte region, NW Italy) within the PRIN-PNRR project "Pierres errantes"

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Keywords: geomaterials, petrography, archaeological heritage.

Petrographic characterization of Roman-era stone artifact samples re-used during the Middle Ages in the Vercelli and Novara areas (Piemonte region, NW Italy), as part of the PRIN PNRR project *Pierres Errantes – Stones Journeys from Classical Antiquity to the Middle Ages, from the Eastern Mediterranean to the Alps*, has been carried out.

The materials analyzed encompass a range of lithotypes of sedimentary, magmatic, and metamorphic origin, characterized by a relatively soft and workable texture, making them particularly suitable for sculptural and architectural applications such as funerary monuments, sarcophagi, capitals, and columns.

To determine their geographical and geological provenance, the samples underwent detailed petrographic characterization, including thin-section analysis using polarized optical light microscopy, scanning electron microscopy (SEM) equipped with an Oxford microprobe (EDS), employing backscattered electron (BSE) and X-ray signals, and cathodoluminescence (CL). These techniques facilitated the identification of main constituent minerals, chemical composition, mineralogical phases, and microstructures.

Petrographic characterization established the identification of general geographical provenance of the stones and, in some cases, their geological domain, unit, and specific quarry site. The study results were cross-referenced with existing petrographic and archaeometric databases in literature, indicating a local origin (from Piemonte region) or from extractive basins in the Alps. In contrast, the characteristics of some rocks suggest a provenance mainly from other areas.

Unsupervised classification of chert from NM-PCI database: testing petrographic and AI feature extraction from images

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Keywords: chert, AI, SOM.

The archaeological issue of the provenance of lithic artifacts or their raw materials requires solid identification of lithotypes through petrographic, paleontological, mineralogical and geochemical analyses. A sound methodological design, which considers all the steps from the sampling to the statistical treatment of data, is of paramount importance for classification and correlation.

Three sets of chert samples of 30 each (Scaglia Rossa Fm, Calcare di Bari Fm, Flysch di Faeto Fm) have been taken as reference for an unsupervised classification test based on data collected according to the nondestructive multiparametric protocol for chert investigation (NM-PCI) and on textural features extracted by digital image analysis (DIA) with Gray Level Co-occurrence Matrix (GLCM) features. Categorical variables were transformed using one-hot encoding to obtain a fully numerical matrix suitable for clustering algorithms.

Three different classification algorithms (hierarchical agglomerative clustering using Ward's method, K-means clustering and self-organizing maps (SOM) with a 3×1 topological map, trained over 100 iterations. Each sample was assigned to a cluster based on the x-coordinate of its Best Matching Unit (BMU). All three algorithms were applied to three datasets: NM-PCI, DIA features, NM-PCI + DIA features. The results obtained show that the SOM algorithm yields the best classifications independently from the database used. A discussion of the output of the different tests will be provided.

Provenance assessment of materials with close geographic relationships: the contribution of an EPR study of the marbles from ancient quarries to archaeological site of Hierapolis in Phrygia (Turkey)

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Keywords: white marbles, Denizli region (Turkey), multivariate statistical data analysis.

The analytical and spectroscopic discrimination of marbles coming from quarries used in historical times is a task object of a wide interest in archaeometric investigations. This task is even more difficult, when the goal of the provenance assessment is focused on marbles coming from historical quarries located in a close geographic area.

The results of a systematic Electron Paramagnetic Resonance (EPR) spectroscopy study are used, in combination with data of isotope geochemistry and petrological observation, to define criteria able to discriminate, firstly, the provenance of 47 marble samples from 5 quarries (i.e. Marmar Tepe, Gölemezli Hierapolis-Gök Dere, Thiounta and Denizli) located in the Denizli region (south-western Anatolia, Turkey) that in Hellenistic and Roman period provided building materials for the nearby city of Hierapolis of Phrygia (Turkey). The extraction areas are geographically very close and, presumably, also geologically related. A similar context asks for the integration of several techniques, in order to disentangle the superposition between the analytical findings and the definition of an accurate protocol for the statistical processing of the data appears needed as well.

The results of the experimental investigation, processed through robust compositional statistical techniques, provide evidence of a good discriminating ability of the proposed approach (Vettori et al., 2024).

With the same approach, 65 marble samples, taken from the buildings of Hierapolis of Phrygia (i.e. Necropolises, North Agora, Sanctuary of Apollo Building A and Stoa of the Springs), have been investigated. The combination of the databases of the quarry and the archaeological samples leads to a reorganisation of the hierarchical contributions, highlighting the petrographic and isotopic parameters able to discriminate, at least partially, the archaeological samples according to their provenance. In particular, an almost certain attribution of Agorà Nord to stones from Gok Dere seems to be substantiated.

Vettori S. et al. (2024) - An EPR study of the marbles from quarries of the Denizli region (Turkey): A contribution to the provenance assessment of materials with close relationships, Microchemical Journal, 202, 110802, https://doi.org/10.1016/j.microc.2024.110802.

S37.

Sustainable management of Cultural Heritage: from diagnosis to innovative protocols for monitoring, restoration and preventive conservation

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Bioconsolidation strategies for carbonate lithologies: effectiveness and mechanisms in calcarenite, travertine, and marble

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Keywords: biomineralization, carbonatogenic bacteria, bioconsolidation.

Biorestoration offers significant benefits for cultural heritage preservation. However, the application of this innovative technique to natural rocks is not fully understood. In this study, we evaluated the efficiency of a carbonatogenic bacterial strain (*Lysinbacillus fusiformis 3.20*) on three natural carbonate rocks: Calcarenite (CA), Travertine (TR) and Marble (MA), having different porosities. We integrated surface analyses (Field Emission Scanning Electron Microscopy, Atomic Force Microscopy, and X-Ray Diffraction) with bulk analyses (Porosity, Ultrasonic Wave Velocity, and Dynamic Elastic Moduli) to investigate the bioconsolidation processes. The results indicated that the biomineralization treatment had no effect on MA samples, while it improved the physical and mechanical properties of both CA and TR, evidenced by the formation of new bioprecipitates. Total and effective porosity decreased, particularly in CA, while ultrasonic wave velocities (Vp and Vs) and Young's modulus increased, with Poisson's ratio remaining unchanged. Comparative observations suggest that connected, randomly distributed, and low aspect ratio pores facilitate microbial activity by enabling deeper bacterial penetration into the stone, supporting nutrient distribution and the formation of calcium carbonate precipitates. When the treatment is effective, stiffness and strength are expected to increase due to reduced effective porosity, while resistance to shear deformation remains nearly constant, as does the relationship between porosity and wave velocities.

Metakaolin-based pigmented geopolymers as filling materials in the conservation of archaeological ceramics

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Keywords: conservation, pigmented geopolymers, archaeological ceramics.

Geopolymers are inorganic amorphous or semi-crystalline materials formed through the reaction between an aluminosilicate precursor and an alkaline activating solution (Leonelli & Romagnoli, 2013). While traditionally applied in industrial contexts, these materials have, over the past few decades, attracted growing interest within the field of cultural heritage conservation, owing to their tunable properties and chemical compatibility with historical substrates. Although previous studies have demonstrated their use as filling materials in ceramic conservation (Fugazzotto et al., 2024; Portale et al., 2024), and surface pigmentation of geopolymers has already been successfully explored (Fugazzotto et al., 2023), the present work introduces a novel approach through the direct pigmentation of light-coloured geopolymer slurries. This enables immediate chromatic integration with the original substrate, removing the need for post-application inpainting.

This study focuses on the development and assessment of pigmented geopolymers based on metakaolin, designed as filling materials for the conservation of archaeological ceramics. The main aim is to offer materials that are compatible, reversible, and visually coherent with historic artefacts, for the filling of *lacunae* in Medieval Norwegian ceramics. Pigmentation was achieved by incorporating selected natural earths and ochres into the geopolymer matrix at concentrations of 1, 3, 6, 9, and 12 wt.%.

A thorough characterisation of both the raw pigments and the pigmented geopolymers was carried out. Techniques employed included X-ray diffraction (XRD) for mineralogical analysis, Fourier-transform Infrared Spectroscopy in ATR and DRIFT modes for molecular insights and scanning electron microscopy coupled with EDS mapping (SEM-EDS) for microchemical investigation. Mechanical performance was evaluated using uniaxial compressive strength (UCS) testing, while moisture interaction was studied through dynamic vapour sorption (DVS). Colourimetric measurements were essential for assessing visual compatibility with ceramic substrates and guided the selection of optimal formulations.

To examine workability, adhesion, aesthetic integration, and reversibility, preliminary tests were conducted using modern ceramic vessels. These tests allowed to establish an application protocol, encompassing both direct modelling of the slurry and use of silicone moulds. The optimized protocols were then applied to archaeological ceramics.

The results reveal that, while further refinement is needed to address shrinkage and microcracking, pigmented geopolymers demonstrate strong potential as filling materials in conservation. Their ease of application, visual harmony with historic ceramics, and reversibility align well with key principles of contemporary restoration practice. These findings support continued research aimed at fine-tuning geopolymer formulations for heritage contexts, potentially offering a sustainable and technically advanced alternative to conventional restoration materials.

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Analytical investigations of iron corrosion from underwater sites: the Nissia shipwreck case study

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Keywords: Archaeometry, shipwreck, corrosion.

The degradation of metallic materials in underwater archaeological sites poses significant challenges for the preservation of cultural heritage. These materials, recovered from ancient shipwrecks, undergo complex physical, chemical, and biological transformations driven by long-term exposure to the marine environment (Bethencourt et al., 2018; MacLeod, 2016). The 18th-century Nissia shipwreck, located at 27 m depth in Famagusta Bay, represents a unique and rare case: the preservation of structural elements, such as metal nails and cannons, make it a key site for studying corrosion mechanisms in underwater contexts. This study focuses on the characterization of metallic artefacts recovered from the shipwreck. Several analytical techniques—including X-ray Powder Diffraction (XRPD), Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM/EDS), and μ-Raman Spectroscopy—are used to investigate the mineralogical composition, microstructure, and corrosion products of these artefacts. The thick corrosion and encrustation layers formed on the surface of iron-based materials offer a unique archive of the long-term interaction between artefacts and the marine environment. They preserve not only traces of artefacts' history but also centuries of transformation after the wreck.

However, this project aims to go further: if shipwrecks show us the result of centuries of corrosion, we are interested in observing the beginning of that story. To achieve this, coupons simulating the composition of the Nissia artefacts have been placed in marine environments, at different sites and depths, where they are being monitored over a 12-month period. These experimental samples act as a time machine, allowing us to observe the early stages of metal decay step by step. Furthermore, coupons are being exposed to controlled pH and temperature conditions simulating future climate scenarios (e.g., acidified waters, increasing temperature (von Schuckmann et al., 2024) to assess how ongoing environmental changes may influence corrosion processes in the coming decades. By combining archaeological materials from the past with experimental models designed for the future, this research aims to build a bridge across centuries of corrosion.

The Nissia case contributes not only to a deeper understanding of degradation phenomena in submerged heritage, but also to the development of diagnostic and predictive tools for conservation strategies in a changing climate.

This research has been funded by European Union's Horizon Europe research and innovation programme under the THETIDA project (Grant Agreement No. 101095253) (Technologies and methods for improved resilience and sustainable preservation of underwater and coastal cultural heritage to cope with climate change, natural hazards, and environmental pollution).

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From diagnosis to conservation: Val di Noto calcarenites and innovative antimicrobial biopolymer membranes

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Keywords: calcarenites, sustainable conservation, stone degradation.

Understanding the degradation behaviour of calcarenites used in baroque monuments in the Val di Noto (La Russa et al., 2015) is crucial for developing compatible and sustainable conservation strategies. This study is focused on three of the most representative building stones of the Baroque architecture of south-eastern Sicily, namely Comiso, Modica and Ragusa calcarenites, on which bio-based membranes incorporating natural antimicrobial agents (Zacchino et al., 2017) have been tested.

Despite their use in historical architecture due to their good workability, these stones exhibit dissimilar responses to physical, chemical, and biological degradation. These differences can be attributed both to varying environmental conditions and to the intrinsic properties of the materials. In this regard, pore distribution, mineralogical composition and mechanical strength play a key role in the progress of degradation forms, included biodeterioration (Cirone et al., 2023). About this, growing environmental awareness is influencing the development of more sustainable strategies, focused on safer and low-impact alternatives to traditional chemical biocides. The differences in degradation behaviour were investigated through a set of diagnostic analyses, namely optical microscopy, ultrasonic velocity measurements, water absorption, mechanical strength and accelerated aging tests by salt crystallisation. The results achieved suggested that Modica calcarenite show greater susceptibility to degradation.

In parallel, polylactic acid (PLA) and chitosan membranes were produced, incorporating essential oils with antimicrobial properties such as limonene, thymol, and menthol to be tested on calcarenites samples. The membranes underwent characterization tests (i.e. FTIR, NMR, contact angle measurements, mechanical tests) to evaluate the functionalization degree. Additionally, biological tests have been also performed to verify the antimicrobial behaviour. FTIR and NMR analyses confirmed the successful integration of the compounds in the membranes. The PLA membranes showed improved flexibility and, in some cases, hydrophobicity.

The biological tests were carried out in Petri dishes by using *Escherichia coli*. PLA membranes showed scarce or no antimicrobial activity, probably because of their poor efficiency in the release of the essential oils' molecules. In contrast, chitosan membranes with limonene and thymol exhibited significant biocidal efficacy. These results encourage continuing our experimentations on antimicrobial biopolymeric membranes by monitoring their performance directly in situ under real conditions.

This study is part of a PhD project cofunded by the CNR institutes: CNR-ICAR, CNR-ITM, CNR-IIT. This work was also financially supported by the project "CarboStone - Le rocce carbonatiche del Barocco Ragusano: caratterizzazione dei materiali e studio del degrado" (PI C.M. Belfiore) within the program PIAno di inCEntivi per la Ricerca di Ateneo 2024/2026, Linea di Intervento 1 "Progetti di ricerca collaborativa" - University of Catania.

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Comprehensive ir multi-method approach for mortars of cultural heritage interest

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Keywords: mortars, FTIR, PCA.

The characterization of mortars in archaeological and architectural contexts is mainly focused on defining the composition, the provenance of raw materials, the degradation products and the causes that led to their degradation. In the last decades, the scientific community has turned to find methodologies and innovative scientific techniques for the analysis and monitoring of these materials, to minimize as possible the sampling and the damage of the works of art.

Among the widely methods in the Cultural Heritage Science, IR spectroscopy provides information regarding the mineralogical composition of geomaterials (Brunello et al., 2019), although its effectiveness can be limited by the complexity and the heterogeneity of samples, resulting in broad and overlapped bands. Even if portable IR instruments enable non-invasive on-site data collection, making it especially valuable for Cultural Heritage studies, the obtained reflectance spectra differ significantly from those obtained using attenuated total reflection (ATR) or transmission modes (which requires micro samples) due to spectral distortions (Miliani et al., 2012; Nodari & Ricciardi, 2019). To evaluate the applicability of ER-FTIR in the study of complex heterogeneous materials as the mortars, ATR, μTransmission (μ-FTIR), and external reflection (ER-FTIR) have been combined with a chemiometric approach and the results have been compared. The ER-FTIR combined with Principal Component Analysis (PCA) elaboration has been evaluated analysing these artificial geomaterial samples, and check if the results helped in defining the raw material provenance, the production techniques. In addition, some samples have been natural and artificial aged and monthly monitored to evaluate the protocol's effectiveness in monitoring degradation progress.

The comparative analysis of the spectra collected aimed to create a comprehensive reference database, enhancing data reproducibility and enabling easier cross-study comparisons. These developments not only improve the characterization and monitoring of geomaterials but also broaden their applications in fields like geology and materials science, marking a crucial advancement in the preservation and understanding of Cultural Heritage. As example of the real application of this multi-method approach, a real case study based on mortars from the Holy Sepulchre in Jerusalem.

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Preliminary findings from a multidisciplinary evaluation of marine-coastal threats to ancient watchtowers in Calabria (Southern Italy)

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Keywords: valorization, 3D model, interactive map.

Calabria's coastal watchtowers, dating back to the Angevin period, became strategic assets during the Viceroyalty of Charles V. Integrated into a broader defence system with castles and fortified cities, they played a crucial role in coastal surveillance and early warning against Turkish attacks (Valente, 1960). Approximately 70 towers, of the originally documented 130, remain today, though most are underutilized and in a state of neglect. This study aims to apply modern technologies to systematically catalogue, evaluate, and promote these historic structures in innovative ways, offering a valuable contribution to their conservation and sustainable valorization. A comprehensive digital map of Calabria's coastal watchtowers has been developed using QGIS open-source software, providing a database that includes information on the conservation status, past restorations, and construction materials of the 70 existing towers. This data is integrated with environmental factors, including lithological map, landslides, and coastal erosion, offering a broader understanding of the challenges faced by these structures. This study focuses on five coastal watchtowers: Saracena (Palmi, RC), Ruggero (Bagnara, RC), Cavallaro (Marina di Gioiosa Ionica, RC), La Rocchetta (Briatico, VV) and Marrana (Ricadi, VV). Preliminary on-site observations have allowed for the identification of their building materials and degradation forms, such as saline efflorescence, alveolisation, *flos tectorii*, and biological colonization (La Russa & Ruffolo, 2021). In order to characterize their minero-petrographic features, several analytical methods will be applied, including Polarized Optical Microscopy (POM), X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), Ion Chromatography (IC), and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS). This research will integrate traditional methods with cutting-edge technologies, including drone-based photogrammetry, to produce highly accurate 3D models of the towers. Furthermore, the study will apply Heritage Building Information Modeling (H-BIM) combined with 3D Geographic Information Systems (GIS) to facilitate a multi-scale analysis and continuous monitoring of the towers condition over time (Colucci et al., 2020). This integrated approach will also enable an assessment of environmental risks and help predict future threats to these heritage sites. Augmented reality (AR) experiences will be realized to foster broader public engagement about the historical and cultural significance of Calabria's coastal watchtowers. By merging traditional research with innovative technologies, this multidisciplinary study supports their preservation and offers a replicable model for sustainable heritage valorization. The outcomes will enhance both the protection and public appreciation of these monuments, contributing to the long-term accessibility and safeguarding of the region's coastal heritage.

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Surficial consolidation techniques applied to artificially-degraded lithotypes used in historic buildings

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Keywords: consolidation, restoration, building stones.

Degradation processes affect all stone monuments and artifacts, even if the effects vary with the lithotype involved, as well as with the exposure to atmospheric agents, the climatic conditions, the urban and industrial pollution and the natural hazards. In the future, climatic change will also contribute negatively to increasing degradation problems in the cultural heritage, therefore actions to restore or prevent damages are necessary.

The lithotypes selected for this study, Lecce stone, peperino from the Alban Hills and sandstone from Camerino formation, are highly different in terms of textural and compositional viewpoints, therefore, the effectiveness of consolidants varies according to the lithotypes.

Sandstone samples have been artificially weathered by heating them at 400 °C for an hour (Franzoni et al., 2013), while peperino samples, after preliminary degradation tests, have been heated at 300°C for an hour. Both lithotypes show strong degradation phenomena. Being the thermal treatment ineffective to degrade Lecce stone, it has been altered by freeze-thaw cycles following the standard EN 12371:2010, although the effects are hardly perceived.

Different eco-sustainable consolidants (i.e. Ethyl silicate, Nanosilica, Diammonium phosphate, Calcium acetoacetate and Nanolime in water dispersion) have been applied according to the possible compatibility of the lithotype, and the effects of the consolidation, evaluated by observations under SEM, have been compared. Surficial colour changes occurred, and alterations were measured by a spectrophotometer. The efficacy and the penetration depth of the consolidants have been investigated by Scotch Tape Test (STT) and Microdrilling Resistance Test (DRMS) (Pondelak et al., 2019). Micro-Computed Tomography (Micro-CT) is being used to assess the variations in volume porosity, pores distribution and micro-fractures before and after the consolidation treatment.

The results showed that consolidation treatments have, in general, contributed to:

- an increase in the surficial grains cohesion;
- porosity and micro-fractures variations;
- slight colour alterations.

Micro-drilling Resistance Test is sensitive to the microscopic variations of the samples: in some cases, if the internal compositional variability of the sample is high, it is not possible to determine the effects related to the consolidation treatments, while in other cases the differences due to the consolidation are evident and the penetration depth could be assessed too. The study revealed how important the use of a variety of methodologies was to investigate the effects of consolidants on the different lithotypes. Also, to better evaluate the applicability of a consolidant, the study highlights that it is necessary to have a deep knowledge of the lithotypes under investigation, and that a close collaboration between different experts is important in the field of materials conservation.

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The construction stones of Megara Hyblaia between the Archaic and Hellenistic periods: degradation and conservation strategies

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Keywords: Megara Hyblaia, construction stone, degradation.

This contribution reports the results of a study aimed at identifying the carbonate lithotypes used as building materials at the archaeological site of Megara Hyblaia (SR), an ancient Greek city founded in 728 BC. The city was depopulated in 483 BC by the Syracusans before being partially reoccupied about a generation later. In 214 BC, the Romans captured the city, but the settlement persisted until the late 1st century BC, after which it was replaced by Roman villae scattered across the former urban territory (Tréziny, 2018). Today, Megara Hyblaia is considered a key example of an early Greek colonial city (Gras et al., 2004).

The study is part of the research activities of the BICAS project, "Building and Inhabiting the City in Ancient Sicily" (2023–2025, PI: F. Mège), inside the Marie Skłodowska-Curie COFUND "GLOBAL_AT_VENICE" programme, which aims to understand how and where the stone was extracted and how it was used in construction. It is also part of the project "CarboStone – Le rocce carbonatiche del Barocco Ragusano: caratterizzazione dei materiali e studio del degrado" (PI: C.M. Belfiore), within the program "PIAno di inCEntivi per la Ricerca di Ateneo 2024/2026, Linea di Intervento 1 'Progetti di ricerca collaborativa'" – University of Catania.

The samples selected for the study were collected from different architectural elements at the site, including columns, capitals, triglyphs, wall facings, funerary steles, and sarcophagus covers. The samples underwent petrographic investigations using polarized light optical microscopy. The compositional and textural features highlighted by these observations, as well as the microfossil associations identified, allowed us to recognize three main lithotypes (ascribable to specific geological formations outcropping in the surrounding area) used in Megarian constructions and to identify several stone quarries as potential sources (Mège et al., 2020). In addition, mechanical tests (uniaxial compressive strength) have been carried out on the three identified carbonate lithotypes, in order to better understand the selection of specific materials in relation to the type of structure or architectural element. Furthermore, a study of the degradation processes affecting these materials is still in progress through hydric tests (water absorption by total immersion and by capillarity) and accelerated aging tests by salt crystallization, in order to identify appropriate conservation strategies for the archaeological structures, which are unfortunately still exposed to atmospheric agents.

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Tréziny H., with Mège F. (2018) - Mégara Hyblaea 7. La ville classique, hellénistique et romaine, 518 pp.

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Proposal of a new in-situ, non-invasive tool for characterizing building stones in archaeological contexts – the Pyrgi case study, Italy

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Keywords: non-invasive analyses, in-situ characterization, ER-FTIR.

When dealing with archaeological finds, analytical strategies that allows to obtain as more information as possible, without the need of sampling, are always desirable. In particular, if the sample to be analysed belongs to an architectural structure, such as a foundation or a building wall that can hardly be sampled or transported, realising a suitable analytical approach becomes challenging. To try to solve this type of problem, a non-invasive and non-destructive procedure has been proposed. Indeed, the combination of portable digital microscopy (Previti et al., 2024) and External Reflectance Fourier-Transform Infrared Spectroscopy (ER-FTIR) (Brunello et al., 2019) can provide adequate information to preliminarily describe and grouping lithic samples as part of building and structures directly on-site. Lithic samples located inside the archaeological site of Pyrgi (Italy) (Baglione et al., 2015) were used as case study: the multi-analytical approach performed in-situ, combining digital images and spectroscopic data, enabled the sorting of the selected samples into distinct groups based on shared characteristics, allowing for a more detailed comparison, and understanding of their properties.

This type of approach allows for a preliminary characterisation of the investigated area, avoiding unnecessary sampling and giving the possibility of concentrating only on particularly interesting or representative samples of each group. In fact, thanks to this approach the number of samples subjected to in-depth destructive analyses was smaller than in a traditional scientific analysis campaign. Some peculiar samples were selected for additional investigation on their mineralogical composition and chemical structure, performing Attenuated Total Reflectance Fourier-Transform Infrared Spectroscopy (FTIR ATR), X-ray powder diffraction (XRPD) and petrographic optical microscopy.

This work is part of the EDIFICIA Project, winner of the Sapienza BE-FOR-ERC 2024 grant, CUP B83C25001000006.

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An innovative approach to compare hydraulic properties of repair mortars and historic mortars: a case study from the historical city center of Catania

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Keywords: mortars, Cultural Heritage, Catania.

Mortars play a crucial role in construction, ensuring mechanical stability, durability, and aesthetic coherence of masonry structures. In the field of architectural conservation, repair mortars are expected to closely match historic materials in their chemical, physical and mechanical properties to guarantee long-term performance. As highlighted in the literature (Schueremans et al., 2011; Belfiore et al., 2023), reproducing historical mortars in the laboratory is essential for understanding their behavior and improving restoration strategies. In this study, we reproduced lime mortars following historical recipes from Catania's architectural tradition, where ghiara, a reddish volcanic aggregate derived from the thermal alteration of paleo-soils by Mt. Etna lava flows, is commonly used. Two experimental formulations were produced by using a 3:1 aggregate-to-binder ratio: one with aggregates in the 2–0.063 mm range and the other one including also the finer fraction (< 0.063 mm), to assess the influence of aggregate grain size on the hydraulic behavior of mortars. The main goal of the research is to compare such experimental mortars with those collected from an external masonry wall of a historic building in the city center of Catania, whose macroscopic appearance reveals a certain variability in both color (i.e. intensity of the red hue) and aggregate grain size. An innovative analytical approach was adopted to identify the hydraulic phases by using Q-XRMA software (Ortolano et al., 2018), which applies sequentially principal component analysis (PCA) followed by supervised maximim likelihood classification (MLC) procedures to SEM-EDS maps to derive the distribution of the Hydraulicity Index (HI) within selected microdomains. Additionally, for the historic mortars, the GIS-based Micro-Fabric Analyzer tool (Visalli et al., 2021) was used to characterize the aggregate grain size and texture from crossed-polarized RGB images via the Grain Size Detector (GSD). Results showed that experimental ghiara mortars generally exhibit better hydraulic properties, with approximately 90% of the binder falling within the range of moderately hydraulic lime to cement, compared to mortars from the historical masonry. The latter exhibit rather variable HI depending on the sampling site and this could be probably due to multiple restoration interventions over time which used different raw materials. Overall, the study highlights the effectiveness of GIS-assisted image analysis in characterizing lime–volcanic aggregate interactions within mortars and offers a solid basis for future research aimed at designing compatible mortars for restoration.

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A multi-analytical investigation of Corinthian Amphorae from Southern Albania with a Terahertz perspective

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Keywords: corinthian amphorae, archaeometry, terahertz technologies.

The present study focuses on the comparative archaeometric analysis of archaeological ceramic sherds from the sites of Butrint and Çuka e Ajtoit (Southern Albania). Recent excavations at both sites have brought to light numerous fragments typologically identified as Corinthian transport amphorae, dated from the 6th-4th centuries BCE. Transport amphorae are renowned preferential items for investigating the ancient world's trade and economy: very often they constitute the only tangible trace of exchanges between cultures (Gassner, 2015). The analysis of their composition and the identification of their provenance are fundamental to identify production sites, which is crucial for the reconstruction of ancient trade routes (Quinn, 2013). Finally, characterising the ceramic sherds allows for a prompt identification of ongoing degradation processes, aiding in the correct planning of the conservation strategy and enabling the best-tailored choice of restoration interventions and materials (Quinn, 2013).

The focus of our research lies in the thorough characterization of the compositional and technological features of these samples through a multi-analytical approach, aiming to obtain information about their production techniques, the provenance of raw materials and the conservation state. Alongside a traditional approach including Optical Microscopy (OM), Fourier-Transform Infrared Spectroscopy (FTIR), and X-ray Powder Diffraction (XRPD), the innovative application of Terahertz (THz) technologies was integrated. THz applications on ancient ceramics are still scarce in the literature, therefore, this work seeks to address this gap.

THz techniques, both spectroscopic and imaging, have seen a remarkable increase in their applications in the neighbouring fields of geosciences, archaeometry, and conservation sciences. This increase is largely due to the particular properties of THz radiation. It lies in a relatively uncharted region of the electromagnetic spectrum, spanning from 1 to 10 THz in frequency and bridging the gap between microwaves and infrared radiation; this region possesses low photon energies (i.e. 4.2 meV at 1 THz), which account for its non-ionizing properties (Huang et al., 2025). These energies excite large-amplitude intermolecular vibrational dynamics in solid-state matter, making THz techniques a powerful yet underexplored tool for the non-invasive and non-destructive characterization of crystalline materials (i.e., inclusions in pottery), especially for their ability to distinguish between polymorphs and to probe microstructural details (Huang et al., 2025).

This study presents the spectral and optical characterization of the ceramic sherds obtained using a THz Time-Domain spectrometer, in both reflection and transmission geometries and employing a customized data processing framework while benchmarking the results against ad hoc acquired spectra of reference mineral specimens.

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Ceramic technologies through time: multi-analytical investigations to explore the ceramic assemblages from Helawa and Aliawa (Kurdistan, Northern Iraq)

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Keywords: archaeological pottery, multi-analytical investigations, past reconstruction.

The archaeological excavation at Helawa and Aliawa (Erbil Plain in the Kurdistan Region of Iraq), carried out between 2016 and 2024, provided a large quantity of potsherds. Systematic surveys have been conducted at Helawa and Aliawa to establish their chronological framework and assess their spatial extent across different periods, and archaeological excavations have uncovered well-preserved stratigraphic sequences of *in-situ* structures and deposits with associated pottery. These layers provided a valuable framework for typological classification of pottery and for examining the evolution of ceramic production and manufacturing techniques over time. Helawa appears to have been a significant prehistoric settlement, abandoned during the Late Chalcolithic 3 and later reoccupied in the Late Bronze Age. In contrast, Aliawa's main occupation dates to the Bronze Age, while during the Hellenistic, Parthian, and Islamic periods, the site probably became a large and fortified settlement. This study was carried out over several years and structured through subsequent phases of analysis, each focusing on a different chronological group of samples to unveil diachronic variations in ceramic production. The assemblages from Helawa and Aliawa reflect distinct manufacturing choices and production techniques, reflecting the local traditions, external influences and evolution in technological knowledge and social structures. The relevant number of samples collected by the Italian Archaeological Expedition of the University of Milan at the Erbil Plain enabled to carry out a comprehensive, multi-analytical characterisation study. The analytical campaign provided data on sherds from the four distinct periods at the Helawa site: Halaf (6000-5300 BCE), Ubaid (5300-4000 BCE), Late Chalcolithic (4000-3000 BCE), and so far, for the Middle Bronze Age (2000-1600 BCE), and the only Late Bronze Age at Aliawa. More than 100 potsherds were analysed using a multi-analytical protocol to investigate the raw material sources, production techniques, and firing conditions of the ceramic samples. The combined use of X-ray powder diffraction (with quantitative phase analysis by the Rietveld full-profile fit protocol) and thin-section petrographic investigation allowed for a comprehensive characterisation of their mineralogical and textural features, revealing different manufacturing processes during the different periods. To further examine the often-decorated surfaces and assess the bulk chemical composition, micro-Raman spectroscopy and X-ray fluorescence analyses were also conducted. The integration of these analytical techniques provided new insights for reconstructing the ceramic production processes at Helawa and Aliawa across the site's different occupation phases, highlighting an evolution in pottery manufacturing practices over time.

Geosciences and the renaissance of a fragile territory: rediscovering the *Campania Felix* through landfill remediation in *Terra dei Fuochi*

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Keywords: rmediation, landfill mining, valorisation of cultural heritage.

The historical name of Campania Felix, a very large territory that extends from Mount Massico to the Campi Flegrei and the Vesuvian area, has been replaced in recent decades by the sadly known "Land of Fires". However, in this fragile context, old landfills offer an opportunity to explore how geosciences can contribute to recovery and sustainability strategies.

The Marruzzella landfill in San Tammaro (CE), for the exclusive definitive storage of unsorted waste (CER code 20.03.01) is now the protagonist of the largest national 'landfill mining' project, which involves the partial emptying of old lots, the recycling of extracted materials and, above all, the recovery of spaces to be used for new landfills.

This will lead, autonomously, to new volumes to which the shredded wet fraction will be allocated, without land consumption and recovering recyclable resources (especially inert materials and metals).

The presence of these sites represents an essential driving force for the study of the geology of the portion of Piana Campana that lies on lands with lithologies attributable both to the volcanic activity of the Campi Flegrei and to the presence of the watercourses of the Volturno and the ancient Clanio (the current artificial canal of the Regi Lagni). In particular, the planning on these sites provides the territorial magnifying glass to define:

- the stratigraphic evolution of the plain.
- the phreatic table, partly poorly represented by regional cartography.
- the hydrogeochemical background, to which widespread reducing areas contribute due to peat degradation.

Management, intervention and planning of the old landfill sites of the land of fires therefore become the fundamental tools for the study of the Campania plain with a holistic approach. In particular, the landfill mining intervention not only aims to reclaim the area, but also to restore environmental integrity, contributing to the protection of the landscape and local biodiversity. This recovery has a clear Economic and Social Impact, especially on local communities, both in terms of public health and socio-economic development. The connection between the landfill and the continuous Real Sito di Carditello offers a unique opportunity, the cornerstone of the intervention, to integrate the conservation of cultural heritage with environmental recovery practices.

The combination of geosciences, environmental recovery and cultural valorization makes the example of Marruzzella a guideline for future similar interventions to be carried out in particular in the so-called "vast areas" of the Campania region, with a redevelopment that aligns perfectly with the objectives of geotourism.

Innovative approaches to reaction path modelling in cultural heritage: preliminary insights into weathering processes

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Keywords: cultural heritage, weathering, reaction path modelling.

Cultural heritage assets are constantly subject to environmental interactions, undergoing transformations often referred to as weathering processes. Climate change represents an additional threat, as it intensifies decay phenomena and contributes to the emergence of new forms of deterioration (Sesana et al., 2021). This research project is based on the experimentation of an innovative method that can support and increase scientific knowledge on the impact of climate change on cultural heritage. The aim of the project consists on the use of Reaction Path Modelling, combined with traditional diagnostic analyses to identify alteration and decay processes. Reaction Path Modelling is an effective method for analyzing geochemical processes, including weathering (Apollaro et al., 2025). By using software such as EQ3/6 and PHREEQC, it is possible to quantitatively predict the formation and/or dissolution of minerals, changes in phase composition, and the distribution of chemical species in geological systems undergoing irreversible reactions between minerals and aqueous solutions, under constant temperature and pressure conditions (Helgeson et al., 1970). In this study, the Reaction Path Modelling is applied to investigate interactions between water and stone materials used in cultural heritage, aiming to quantify mineral dissolution and secondary product formation. The methodological framework included: i) the selection of four pilot sites in Calabria (Italy), characterized by granitoid and carbonate lithologies located in urban and coastal contexts; ii) the collection and analysis of environmental data (temperature, precipitation, and CO_2 concentrations) obtained from local monitoring stations; iii) the petrographic characterization of the lithotypes to define the solid phase for geochemical simulations. An initial simulation focused on the dissolution of calcite in a selected pilot site characterized by limestone lithology. To this end, PhreeqC (Charlton & Parkhurst, 2002) software is used, entering input data regarding monthly atmospheric CO_2 data, the site's mineralogical composition, and historical monthly average temperatures. The models provide the amount of calcite dissolved as a result of geochemical interactions. This value is then normalized using the monthly mean precipitation for the site, resulting in a final output expressed as the amount of calcite dissolved per square meter of exposed surface. The results provide an initial interpretative framework for weathering phenomena affecting carbonate stone materials and demonstrate the applicability of the method to other case studies. The ability to correlate degradation processes with current and future environmental conditions offers valuable data for predicting their evolution in the context of climate change.

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Charlton S.R. & Parkhurst D.L.(2002) - PhreeqcI-A graphical user interface to the geochemical model PHREEQC. U.S. Geological Survey, No. 031-02.

Helgeson H.C. at al. (1970) - Calculation of mass transfer in geo-chemical processes involving aqueous solutions. Geochimica et Cosmochimica Acta, 34(5), 569-592, https://doi.org/10.1016/0016-7037(70)90017-7.

Sesana E. et al. (2021) - Climate change impacts on cultural heritage: A literature review. WIREs Clim Change 12(4), e710, https://doi.org/10.1002/wcc.710.

Non-invasive spectroscopic approach for the determination of emerald provenance

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Keywords: emerald, spectroscopy, provenance.

Emerald is a cyclosilicate belonging to the beryl-group with the general formula $Be_3Al_2Si_6O_{18}$ and owes its colour to the presence of Cr^{3+} and V^{3+} as minor or trace elements (Aurisicchio et al., 2018). Emeralds have always been considered precious gems throughout history, as evidenced by their widespread distribution in antiquity even far from their mines. Given their value, it is essential to establish a non-invasive analytical procedure applicable to emerald provenance studies. Fourier Transform Infrared Spectroscopy (FTIR) has proven to be a useful non-invasive approach (Branca et al., 2020), thanks to the shape and position of vibrational modes associated with the Si-O stretching (main peak ~1200 cm^{-1} and shoulder at ~1140 cm^{-1}) and the bands associated with the OH stretching mode of water (in the range 3500-3800 cm^{-1}) which can help in the definition of their provenance. Alongside the advantages offered by non-destructive techniques, it is also important to consider their limitations and drawbacks. In many cases, certain emeralds could not be analysed due to the small size of the samples. In other instances, surfaces rich in inclusions made the analysis challenging. Additionally, for this specific analytical technique to yield high-quality external reflection IR spectra, the samples must have perfectly smooth surfaces. The possibility to analyse various gems from major deposits enabled the collection of a comprehensive set of spectroscopic data. Emerald samples from Afghanistan (Pajshir Valley), Egypt (Gebels Sikaït, Zabara), Ethiopia, Nigeria (Jos, Gashala), Pakistan (Swat Valley), and Russia (Urali) were analysed using External Reflectance (ER) FTIR and μ-FTIR in transmission mode. The combined analysis of score scatter plots and loading plots facilitated the identification of significant spectral bands for ER-FTIR (primarily in the 850–1300 cm^{-1} range) in the analyzed emerald samples, offering insights into fundamental vibrational modes useful for distinguishing among different provenances. The dataset was processed using a statistical approach—Principal Component Analysis (PCA)—which supports the standardization of parameters for effective provenance discrimination. The combined use of non-destructive and non-invasive analytical techniques (fundamental in the field of cultural heritage) and multivariate statistical analysis (PCA) has produced innovative results in a domain where preserving the integrity of analysed artifacts has to remain a priority.

Aurisicchio C. et al. (2018) - Major and trace element geochemistry of emerald from several deposits: Implications for genetic models and classification schemes. Ore Geology Reviews, 94, 351-366, https://doi.org/10.1016/j.oregeorev.2018.02.001.

Branca C. et al. (2020) - Combining Fourier transform infrared and Raman spectroscopies with Gaussian deconvolution: An improved approach for the characterization of emeralds. Journal of Raman Spectroscopy, 51(4), 693-701, https://doi.org/10.1002/jrs.5810.

Evaluation of different strategies for in-situ preservation of dinosaur footprints at the Sezze ichnosite (Latium, central Italy)

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Keywords: dinosaur footprints, ichnosite, conservation.

Geoheritage represents an essential segment of natural heritage, encompassing a range of geological resources with scientific, cultural and educational significance. Among these, ichnosites, which preserve footprints and traces left by organisms during their lifetime, are of particular importance for understanding the evolutionary and paleoenvironmental history of extinct terrestrial tetrapods (García-Ortiz et al., 2014). Sezze ichnosite (about 70 km south of Rome) is characterised by over 230 dinosaur footprints preserved on three distinct bedding surfaces in the abandoned Petrianni Quarry, representing to date the most extensive dinosaur tracksite in central Italy (Nicosia et al., 2007; Petti et al., 2020; Antonelli et al., 2023). The track bearing surfaces are continuously affected by exogenous agents and the theropod and sauropod footprints are significantly degraded and at serious risk of being obliterated due to ongoing natural processes. To develop a long-term strategy for in-situ preservation, various approaches were tested on mock-ups simulating dinosaur footprints to evaluate their effectiveness. The consolidants used included two commercial products (Siox5 RE50 and NanoEstel) and two experimental formulations (TEOS with chitosan nanoparticles and a chitosan-based solution). Additionally, a bioconsolidation process was tested using carbonatogenic bacteria isolated from the ichnosite and identified as *Lysinibacillus fusiformis* strains. To assess the durability of consolidant treatments to acid rain exposure, the samples were partially immersed for a month in a 10^{-4} M sulfuric acid solution. The mock-ups were analysed using optical microscopy, scanning electron microscopy, peeling test and colorimetry. A digital comparison of mock-up surfaces before treatments, after consolidant application and after artificial ageing was performed using high-detail 3D models produced by *Structure from Motion* (SfM) photogrammetry. The results show differences in the adhesion and durability of the protective layers formed on sample surfaces by each consolidant, allowing the evaluation of their suitability for in-situ application.

Antonelli M. et al. (2023) - Inferred oviraptorosaur footprints in the Apenninic Carbonate Platform: New tools for the identification of trackmakers from the Sezze ichnosite (lower-middle Cenomanian; central Italy). Cretaceous Research, 141, 105362, https://doi.org/10.1016/j.cretres.2022.105362.

García-Ortiz E. et al. (2014) - Concepts and terminology for the risk of degradation of geological heritage sites: fragility and natural vulnerability, a case study. Proceedings of the Geologists' Association, 125(4), 463-479, https://doi.org/10.1016/j.pgeola.2014.06.003.

Nicosia U. et al. (2007) - Dinosaur Tracks as Paleogeographic Constraints: New Scenarios for the Cretaceous Geography of the Periadriatic Region. Ichnos 14, 69-90, https://doi.org/10.1080/10420940601006859.

Petti F.M. et al. (2020) - Cretaceous tetrapod tracks from Italy: a treasure trove of exceptional biodiversity. Journal of Mediterranean Earth Sciences, 12, 167-191, https://dx.doi.org/10.3304/jmes.2020.16873.

For a sustainable monitoring and preventive conservation protocols of submerged cultural heritage: results from the ongoing SOUTH Project

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Keywords: submerged cultural heritage, antifouling treatments, image processing.

The SOUTH project - Safeguard Of sUbmerged culTural Heritage - aimed an innovative and sustainable in continuous monitoring system to evaluate to recognize, before the macroscopic perception, the onset of forms of degradation that develop on stone materials typically present in submerged historical/archaeological sites.

The initial phase of the project's experimentation, commencing with a comprehensive review of existing literature [1-3], has been started from testing innovative formulations aimed at protecting the stone materials (marble and limestone samples) from biofouling by monitoring the growth and progression of damage over time. Antifouling treatments have been selected and tested: magnesium oxide (MgO), Chitosan, pure and in 50% mixture, are applied on exposed surface of samples. Investigations have been started to characterize the selected raw materials, evaluating their performance before and after application on stone samples and after permanence in a simulated aquatic environment, at scheduled steps. UV-induced visible fluorescence (UVF) imaging investigation are carried out to distinguish, thanks to specific red spectral emission, the biofilm that grow on the stone substrate over time. UV LED filtered at 365 nm have been used as radiation source and UV-induced luminescence images are captured by a CCD digital camera for capturing images within the VIS range to detect visible fluorescence emission. Moreover, the biofilm growth on exposed samples in the experimental laboratory microcosm, is monitored through photographic image acquisition. These several images, recorded on a weekly basis, at different distances and shooting angles, are treated by image processing and machine learning algorithms. Among the project objectives, the automated monitoring phase using advanced image processing methods is crucial. Improved processing techniques and machine learning algorithms will help minimize the noise of underwater images and facilitate the analysis of microbial growth based on data collected both in the laboratory and in situ. This automated approach will enhance monitoring efficiency making the preventive conservation more sustainable, allowing for the assessment of materials without the need to extract samples from the aquatic environment. The main objective is to analyze and compare damage to different stone materials exposed to seawater over an extended period while assessing the efficacy of new protectives against biofouling by comparing the degradation effect on non-treated marble and limestone samples. After the pilot tests, the antifouling treatment and the automated processing image will validate at a submerged site in Southern Italy. Indeed, thanks to the replicability and scalability of the designed protocols, the methodological solutions developed within the SOUTH framework could potentially be applied to other historical and archaeological sites across the Mediterranean facing similar conservation challenges.

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Landslide hazard evaluation strategies for safety improvement and conservation of unstable small towns of the southern Apennines

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Keywords: landslides, historical towns, conservation.

The Apennine Mountains of southern Italy are disseminated of historical small towns, which form a unique cultural heritage known worldwide. Despite this, many of these settlements are experiencing rapid depopulation and progressive architectural and environmental decay, driven in large part by landslide processes damaging historical buildings and infrastructures. Safeguarding their cultural, social, and economic value demands a multi-disciplinary scientific strategy based on the understanding of landslide predisposing and triggering factors and the analysis of long-term evolution, including the influence of ongoing climate change. Within this framework, this work presents a study developed in the context of the PRIN LIVES project (*LIVing in unstable historical towns: landslide hazard Evaluation Strategies for safety improvement and conservation*) aimed at coping with this challenge through: i) identification of representative unstable historical towns in Southern Italy; ii) monitoring and mapping damage to historical buildings; iii) analysis of landslide hazard by the reconstruction of engineering-geological slope models; iv) identification of triggering factors and displacement prediction; iv) definition of mitigation strategy. The research activity is focused on three representative historical towns of the southern Apennines: Civitacampomarano (Molise), Lauria (Basilicata), and San Lorenzo Bellizzi (Calabria). These towns lay in complex geological and geomorphological settings and have historically been affected by different types of landslides resulting in severe damage to historical buildings. The identification of the study sites was achieved through displacement time series of the available Persistent Scatterers (PS), derived by the ERS (1992-2000) and ENVISAT (2002-2010) satellite data provided by *Piano Straordinario di Telerilevamento Ambientale* (PST-A). Sentinel-1 PS data (2015-2018) from European Ground Motion Service were also considered. Ascending and descending geometries, with a displacement threshold of -2/2 mm/y, were both analyzed.

As a result, the spatial distribution of displacement rates, their zonation in the urban areas of small towns, recognition of acceleration patterns, and possible links with rainfall events were assessed. Field investigations to define damage intensity on historical buildings, analysis of their spatial distribution, and interviews to the inhabitants about the landslide risk perception were then conducted. For these case studies, the geological-engineering model and landslide phenomena were reconstructed through surveys, aerial photogrammetry, InSAR data, and pre-existing maps.

The results provide insights into landslide processes, which are fundamental for planning monitoring, stabilization, and conservation interventions of the architectural heritage for the investigated areas. Considering that the developed strategies were evaluated in different geological and geomorphological settings, they represent a reference also for the analysis of other historical contexts of the southern Apennines.

Development of sustainable lime mortars using Rice Husk Ash for the conservation of cultural heritage

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Keywords: lime-mortars, rice-husk-ash, agro-wastes

Today, billions of tons of agricultural waste are produced every year (Mengqi et al., 2023). Among these, crop residues represent the most abundant source of organic waste, with corn, wheat and rice being the main contributors. Embracing the circular economy enables sustainable waste management by transforming waste into valuable resources, thus reducing environmental impact and supporting resource efficiency (Muscat et al., 2021). This study investigates the potential use of agricultural by-products - specifically rice husk ash (RHA) - in lime-based mortars for the conservation of cultural heritage. The research was structured into three phases: the production and characterization of the ashes, the evaluation of their pozzolanic reactivity, and the formulation and testing of RHA-based mortars. In the first phase, the influence of burning temperature (500 °C, 600 °C, 700 °C, and 800 °C) on RHA characteristics was assessed using XRD, XRF, LOI, SEM-EDS, and BET analyses. The second phase focused on determining the pozzolanic reactivity of the ashes in lime pastes through Thermogravimetric Analysis (TGA), FT-IR spectroscopy, and SEM-EDS, with special attention to portlandite consumption and the formation of calcium silicate hydrate (C–S–H) phases. The third phase involved the formulation and testing of mortars incorporating the most reactive ash, combined with hydrated lime and standard siliceous sand. The mechanical and physical properties of the newly developed mortars were evaluated through standardized testing. Results show that RHA remains amorphous up to 700 °C, with a silica content exceeding 87%. Regarding the reactivity, FT-IR spectra and SEM-EDS analyses confirmed the presence of C–S–H phases in all samples. Notably, pastes containing 500 °C RHA exhibited the highest reactivity, with complete $Ca(OH)_2$ consumption within 14 days. Consequently, 500 °C was identified as the optimal combustion temperature for mortar production. Mortars incorporating 500°C RHA demonstrated promising results, with performance in many cases comparable to NHL 3.5 reference mortars.

Mengqi Z. et al. (2023) - Comprehensive review on agricultural waste utilization and high-temperature fermentation and composting. Biomass Conv. Bioref., 13, 5445-5468, https://doi.org/10.1007/s13399-021-01438-5.

Muscat A. et al. (2021) - Principles, drivers and opportunities of a circular bioeconomy. Nat. Food, 2(8), 561-566, https://doi.org/10.1038/s43016-021-00340-7.

S38.

Geosciences at School

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"Geosciences and the Environment" PLS articulate proposal from DISTeGeo at UniBa

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Keywords: PLS Scienze Geologiche UniBa, secondary school, Geosciences.

As part of the National PLS 23/25 Project, the Dep. of Earth and Geo-Environmental Sciences (DISTeGeo) at the Univ. of Bari Aldo Moro (UniBa) developed its own project, focusing particularly on Action C "Lab. Practices" and Action E "Professional Development of Secondary School Teachers". The project offered the opportunity to present topics closely linked to Geoscienses by integrating them with environmental themes internationally promoted by the ONU (e.g., World Geodiversity Day, International Day of Women and Girls in Science, World Water Day).

The strength of the proposal *"Geosciences and the Environment"* lies in its flexible structure, allowing institutions and teachers to select the activities and number of hours that best suited their needs. Each course generally included about 20 hours, divided into two-three lab sessions held at schools, a visit to DISTeGeo (including a guided museum tour and lab activities), a field trip and a final meeting during which students, organized into working groups, developed a final product (e.g., a PPT presentation or video clip). The topics chosen by the schools covered the whole spectrum of Geosciences and the initiatives reached approximately 750 students from 15 different secondary schools. Best feedback was obtained especially when a close cooperation and interrelationship was established between the experts and school tutors or teachers which actively participated to the proposed activities.

Field excursions sparked considerable interest, including geosites such as Gravina town, abandoned bauxite mines or the natural reserve of Margherita di Savoia Salt Pan or historic center of the city where the school is located.

During the field trip in Bari's and other Apulian historic centers, students and their teachers had the opportunity to explore the old town from a new perspective. They observed firsthand how the typical rocks of the Apulian bedrock (Cretaceous limestones and Quaternary calcarenites) have been used over the centuries to build historical and religious monuments. They also examined different ornamental stones found along the city's main shopping streets. An interactive game using smartphones challenged students to identify the main rock types based on their observations of building facades and pavements.

The project also involved master's and PhD students to ensure generational closeness with the young participants. Educational and information materials were prepared and distributed. Students enrolled in the Bachelor's Degree in Geological Sciences at UniBa also provided valuable support to DISTeGeo activities.

Several initiatives targeted secondary school teachers, aiming to strengthen their skills in Geosciences, a field in which many of them, with backgrounds in Chemistry and Biology, have limited training. Seminars, field trips, and laboratory activities were organized both in schools and at DISTeGeo, attracting many enthusiastic and motivated teachers eager to fill gaps in their Earth Sciences knowledge.

To beach or not to beach? A citizen science project to monitor sand beaches

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Keywords: sand beaches, citizen science, mining.

Sand has become a vital commodity for our modern economies. This material, which we often take for granted, is extracted worldwide at a rate that the tipping point has been already passed from an environmental, social and economic point of view (Rangel-Buitrago et al., 2023). This extraction, at a rate far more than the system's renewability (Beiser, 2018), is having a severe impact on rivers, deltas, coastal and marine ecosystems around the world, resulting in land loss, lowered water tables, decreased sediment supply, widespread habitat degradation and loss of biodiversity (UNEP, 2022). The absence of global aggregate extraction data makes environmental assessment very difficult and has contributed to the lack of awareness on this issue, which in turn results in a lack of action. There is in fact a large discrepancy between the extent of the problem and public awareness. As this is a highly topical issue (Pilkey et al., 2022), citizens should be directly involved through a Citizen Science approach in mapping and monitoring beaches along marine-coastal zones. We focused on this geomorphologic element by capturing its dual significance as a well-known, loved and frequented environment on the one hand, but a threatened, fragile interface, like other forms of the landscape, on the other.

Beaches are transition zones, and their evolution and morphological characteristics are the result of a combination of marine processes. Thanks to these characteristics, they are perfect indicators of sand mining activities both along rivers and in the sea. In fact, there are various criteria to distinguish and classify beaches, including, topographic gradient, sediment origin, grain size and predominant sedimentary processes. We started to use these criteria to build an 'identity card' for each beach to help citizens understand its characteristics, its state of health (bio-geo-diversity vs. tourist impact) and any risks it runs (erosion, contamination). The identity cards gradually created with the help of citizen scientists, trained by researchers, should populate an online catalogue that will allow them through an APP to be better known and monitored. The objectives of this initiative include: identification of factors triggering coastal erosion and disappearance of beaches/dunes; quantification of effects of tourist exploitation on their stability/health; raising awareness among local administrations/stakeholders; promote change of behaviours/attitudes; contribution to shared coastal zone management strategies; building evolutionary scenarios in the context of climate and environmental changes. We used an interdisciplinary approach along pilot marine-coastal areas in the Mediterranean Sea starting from: 1) analysis of the state of the art; 2) field activities; 3) lab analysis; 4) involvement of local communities; 5) dissemination and communication. In this session, we will present and discuss this initiative and first achievements.

Beiser V. (2018) - The World in a Grain: The Story of Sand and How It Transformed Civilization. Riverhead Books, 294.

Pilkey O.H. et al. (2022) - Vanishing sand: losing beaches to mining. Duke University Press, Durham.

Rangel-Buitrago N. et al. (2023) - The global impact of sand mining on beaches and dunes. Ocean and coastal management, 235, 106492, https://doi.org/10.1016/j.ocecoaman.2023.106492

UNEP (2022) - Sand and sustainability: 10 strategic recommendations to avert a crisis. GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland, https://unepgrid.ch/storage/app/media/Publications/2022sandandsustainabilityreportfinal.pdf.

Geosciences Education through Integrated Fieldwork and Laboratory Practice: A Case Study from Liceo Galilei

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Keywords: geoscienze education, school-university collaboration, field-based learning.

Since September 2023, the Liceo Scientifico "Galileo Galilei" in Potenza, Southern Italy, has been coordinating a national-level educational initiative in collaboration with the University of Basilicata. The project is designed to promote geoscientific literacy among high school students, with the primary objective of fostering competencies in geology, geophysics, and geochemistry through the implementation of innovative, laboratory-based teaching methodologies. A key aim is to inspire students to pursue further academic and professional pathways in the geosciences.

The program seeks to broaden students' engagement with both classical and contemporary geoscientific topics. In addition to foundational concepts such as lithogenesis, continental drift, and geological time, the curriculum also addresses pressing modern issues, including land-use planning, environmental challenges, the assessment of natural and anthropogenic risks, and the sustainable exploitation of renewable energy resources.

Spanning three academic years, the project comprises a total of 120 instructional hours (40 hours annually) and is targeted at students in the 11th grade and higher. Each year, students will participate in 17 hours of instruction at the Liceo Galilei, 15 hours of laboratory activities at the University of Basilicata, and 8 hours of fieldwork at key geosites across the Basilicata region. Field destinations include, among others, the Latronico geothermal power plant, the Vulture volcanic complex, and the clay badlands of Aliano.

Upon completion of the program, students are expected to have significantly enhanced their understanding of Earth Sciences and to have developed a deeper awareness of the discipline's pivotal role in informing policy decisions related to land management and the sustainable utilization of natural resources.

The shapes of water: a geological and environmental investigation of the Castellano Stream

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Keywords: environmental education, geological investigation, river ecosystem.

The project was carried out as an Environmental Education Laboratory within a school initiative called "AscolINatura" between April and May 2024. Its goal was to promote knowledge, respect, and appreciation of the natural environment surrounding the D'Azeglio Lower Secondary School in Ascoli Piceno. The primary site for observation and study was the river park of the Castellano stream, a right-bank tributary of the Tronto River, which flows through the city and runs near the school building.

Second-year students were engaged in a structured program of outdoor activities and scientific workshops, designed and conducted in collaboration with the company Geoinside s.n.c. of Ascoli Piceno. This collaboration enabled the analysis of the water's chemical-physical parameters and the collection of a river sediment sample for grain size analysis. The fieldwork experience allowed students to observe and interpret the natural environment using simple scientific field tools, fostering technical and scientific skills through direct investigation.

The educational activities included an analysis of the river ecosystem, with particular focus on the geomorphological and hydrogeological aspects of the watercourse, the study of sedimentary dynamics, the recognition of landscape features related to fluvial processes, and the observation of changes caused by natural events and human interventions. Students also collected and examined benthic macroinvertebrates, used as bioindicators to assess the ecological quality of the water. This helped them develop awareness of the importance of biodiversity and the protection of aquatic environments.

The laboratory fostered an integrated approach to the natural sciences, incorporating topics related to civic education, active citizenship, and sustainable development.

The main objective of the project was to guide students in understanding the geological and geomorphological processes at work in their local area, helping them to develop a scientific perspective and recognize geology as a key to interpreting the landscape. It also aimed to raise awareness of their role as responsible citizens, starting from a deeper knowledge of their local environment.

Where rocks shape life: exploring geodiversity and biodiversity in the Regional Park of Apuan Alps

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Keywords: Apuan Alps, geodiversity, education.

"A Passport for the Park" is an environmental education project that won first place in the Alfredo Lazzeri competition, organized by the Apuan Alps Regional Park Authority as part of its 2023/24 educational offer for schools. The initiative was developed by students from classes 3F and 4F of the Environmental Biotechnology track at IIS Zaccagna-Galilei in Carrara, under the guidance of their teachers in Biology, Microbiology, and Environmental Control Technologies, along with Dr. Ilaria Furfori, from the University of Pisa.

The project aimed to explore the interdependence between geodiversity and biodiversity by focusing on two important sites in the Apuan Alps: the "Pellegrini-Ansaldi" Botanical Garden in Pian della Fioba and the karst cave "Antro del Corchia" in Levigliani. These locations serve as natural laboratories, where the sharp contrast between siliceous and calcareous substrates influences soil properties, vegetation, and overall ecological dynamics. The students observed firsthand how the geological evolution of the region — shaped over 200 million years — directly impacts local ecosystems (Carmignani et al., 2006; Montomoli et al., 2016).

The botanical garden at Pian della Fioba showcases different plant communities based on the underlying lithology. Siliceous areas, which retain more water, host species such as Abies alba and Ilex aquifolium, while calcareous areas, which are drier, support specialized species like Globularia incanescens and Saxifraga callosa (Ansaldi, 1990). This interplay between geology and biology formed the basis of the project's investigation.

Through an interdisciplinary approach, students engaged in a range of scientific activities, including the analysis of rock samples, landscape interpretation using geological maps and Google Earth, and fieldwork with park experts. They documented their findings through photographs, environmental data sheets, and educational podcasts, and created a "passport" for the botanical garden to make its geological and ecological significance accessible to a wider audience.

The project, carried out from May to November 2024, enhanced students' scientific awareness and ecological responsibility. It encouraged reflection on the fragile nature of ecosystems, the importance of conservation, and sustainable resource use. The students created a virtual tour of the garden and a public outreach poster, transforming complex geological and biological concepts into understandable material for the general public.

In line with the 2023/24 educational theme "Educating in the sciences to mitigate climate change," the project aimed to nurture future generations of environmentally conscious citizens, starting with the rich and unique landscapes of the Apuan Alps. By exploring these sites, students became more aware of the relationship between the Earth's geological processes and the biodiversity that sustains life.

Ansaldi M. (1990) - Orto Botanico di Pian della Fioba.

Carmignani L. et al. (2006) - Lineamenti geologici delle Alpi Apuane. Acta Apuana, 5, 9-23.

Montomoli C. et al. (2016) - La tettonica delle placche: scopriamo l'oceano ed il continente sulle Alpi Apuane (PLS, DST-Pisa).

Unearthing learning: transforming abandoned urban green spaces into geological classrooms

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Keywords: urban green spaces, education, rock garden.

The regeneration of abandoned urban green spaces offers a strategic opportunity to combine ecological restoration with public education. In the Lazio region, renowned for its geodiversity and historical heritage, such spaces can be repurposed into educational and outreach areas that enhance both scientific literacy and environmental stewardship. This need is even more crucial in the city of Rome to bring citizens, in particular high school students and educators, closer to natural environments to build a robust culture of Sustainability. The project proposes the transformation of a neglected green area located in the eleventh municipality of Rome, into an open-air learning environment, focused on the geological features of Lazio. The initiative aims to develop thematic trails, outdoor laboratories, based on the design and implementation of an articulated Rock-Garden that communicates key aspects of geological evolution of Lazio, including:

the main tectono-stratigraphic domains (recording paleo-environments and paleo-climates) developed, first, along the southern Tethyan margin and, second, during and after the Apennine mountain building, over about 200 million years history;

the volcanic processes and successions of the main volcanic districts developed since Pleistocene times along the peri-Tyrrhenian margin.

These elements serve as the basis for interdisciplinary learning experiences tailored to students, teachers, and the wider public. Through hands-on activities and guided exploration, the public will gain a deeper understanding of the region's geological evolution, its relevance to current environmental challenges (e.g., concerning natural risks and resources, links between natural and historical heritage). By embedding geological interpretation within regenerated urban spaces, the project supports outdoor education, enhances community engagement, and contributes to urban sustainability. In this context, the project offers resources and infrastructure to support experiential, curriculum-linked teaching in an accessible urban context. In doing so, it encourages educators to incorporate local environmental knowledge into their teaching practice and to use the city itself as a dynamic learning environment.

The broader goals of the initiative include environmental restoration, social inclusion, and the creation of resilient green infrastructure. The collaborations between the eleventh municipality of Rome and the University of Roma Tre, ensured scientific accuracy, public accessibility, and long-term maintenance. Ultimately, the project demonstrates how geology-based education can serve as a catalyst for urban renewal, fostering both environmental awareness and active citizenship.

Fantasy taxonomy in STEM education: a case study inspired by *How to Train Your Dragon*

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Keywords: ludic learning, learning by doing, fantasy-taxonomy.

School systems are constantly evolving, adapting to societal changes and, along with them, to the transformations experienced by children and adolescents. As part of this evolution, new educational initiatives continuously emerge to enrich, enhance, and deepen student learning—particularly within the STEM disciplines. Within this dynamic landscape, a unique project came to life almost by chance. It eventually led to the development of a systematic review and the construction of a phylogenetic tree. While these tools are essential in biology and paleontology, they often prove challenging for students who have not yet acquired the necessary cognitive tools. To make these complex scientific methods more accessible, we designed hands-on science activities based on "fantasy-systematic" and "fantasy-phylogenetic" studies. Drawing inspiration from the How to Train Your Dragon cartoon, students engaged in tasks centered on the systematic and taxonomic classification of dragons featured in the series. A total of 46 students, aged 11 to 14, participated in the project. The activities were carried out in a learning-by-doing context, where students became active protagonists of their own learning, turning theoretical knowledge into practical skills. The main objective was to revise the classification of dragons using authentic Linnaean taxonomy criteria—presented creatively and accessibly for learners of all ages. A total of 74 dragon species were studied and grouped into different fantasy dragon families. In addition, students created the "Dragon Tree", a fantasy phylogenetic analysis aimed at identifying evolutionary relationships and degrees of kinship among the species depicted in the literary and cinematic universe. Though clearly a creative exercise framed within a scientific context, the project had a meaningful impact. It was both educational and engaging to witness students discussing phylogeny, evolution, and taxonomic relationships… among dragons.

Evolution of environmental topics in school textbooks: a comparison from 1970's to present

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Keywords: environmental topics, school textbooks, geosciences.

Since the 1970s, environmental issues have become increasingly important on a global scale. Education plays a key role in making young people aware of anthropic impact on the environment (Orion & Libarkin, 2023) and in this context the use of textbooks for teachers and students is very important (Brusi et al., 2016). Therefore, we decided to investigate how Geosciences textbooks reflect this change by analysing successive editions for upper secondary schools from the 1970s to the present.

Our analysis shows that, in the 1970s editions, the main focus is on the geological description of natural phenomena, with less attention paid to anthropogenic impacts.

In the editions of the 1980s, more attention is paid to global warming and air pollution, correlations between population growth and fossil fuel consumption, and broadening environmental implications.

The editions of the 1990s expand coverage of sustainability and resource management policies, with references to global strategies, recycling and resource depletion, highlighting their economic and social impacts.

Between 2000 and 2018, the texts take a systematic approach, including Agenda 21, the Kyoto Protocol and IPCC climate change models. Resources and reserves are deepened, linking energy consumption and population growth.

In the editions of the years 2019-2024, the texts incorporate the themes of the 2030 Agenda, as the 2019 law introduces the new regulation of the teaching of Civic Education at school, one conceptual core of which is 'Economic Development and Sustainability'.

The comparison among editions shows a definite evolution in dealing with environmental topics , from a view focused primarily on natural processes to a more integrated approach towards global and social issues: over time, sensitivity to the environment has changed, leading to a broader view that also considers social and global aspects and their interconnections. Since the 2000s, the approach has become increasingly integrated, linking environmental issues with economic, ethical, political and social ones. In this way, sustainability is not only about nature, but also about people's lives and global balance. Over the various Geosciences textbooks since the 1970s, there has been a gradual evolution in the treatment of geology, climatology and natural resources topics, reflecting a change in environmental awareness and educational approaches. Indeed, the focus on global warming, pollution and sustainability increases significantly over time, in parallel with the growing international concerns and environmental policies adopted. In conclusion, we can say that sustainability education is gradually emerging, reflecting a shift in pedagogical priorities in line with international commitments and global challenges (Gill, 2017; Metzger, 2024). This comparison underlines the crucial role of textbooks in shaping environmental awareness and responsible resource management in students and teachers.

Brusi D. et al. (2016) - Textbooks: A Tool to Support Geosciences Learning. In Vasconcelos, C. (eds) Geoscience Education, Springer, Cham, 173-193, https://doi.org/10.1007/978-3-319-43319-6_10.

Gill J.C. (2017) - Geology and the Sustainable Development Goals, Episodes, 40, 70-76, https://doi.org/10.18814/epiiugs/2017/v40i1/017010.

Metzger E. (2024) - Reimagining Geoscience Education for Sustainability, Earth Science, Systems and Society, 4, https://doi.org/10.3389/esss.2024.10116.

Orion N. & Libarkin J. (2023) - Earth Science Education. In Lederman N. G., Zeidler D. L., Lederman, J. (eds), Handbook of Research on Science Education, New York: Routledge, 692-716, https://doi.org/10.4324/9780367855758.

A journey into prehistory: the educational experience at the archaeological site of Lamalunga (Altamura)

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Keywords: interdisciplinary education, heritage valorization, sustainable development.

In February 2025, The Natural Science teachers Stefano Benedetto and Lucia Genchi from the Science Department of the "Galilei – Curie" high school center in Monopoli (BA) organized two educational visits to the Lamalunga archaeological site, each involving two 4th-year classes. Located in the heart of the Murgia region near Altamura, Lamalunga offered students a highly enriching learning experience, immersing them in the fields of prehistory, geology, and anthropology. This remarkable site, renowned for its fossil remains and archaeological discoveries, lies close to the Lamalunga Cave—where the famous Altamura Man was found—providing an exceptional context for exploring human evolution and reconstructing past ecosystems through direct observation and interpretation of cultural and natural heritage. The experience was designed not simply as a content-based outing, but as an opportunity to develop both disciplinary and cross-curricular skills aligned with the objectives of 21st-century education. At the end of the visit, students took part in a creative, interdisciplinary workshop that produced a variety of outcomes: scientific posters, digital presentations, narrative and poetic texts inspired by the visit, graphic logos, and multilingual translations (Italian, English, Spanish), all reflecting a personal and collective reworking of the experience. The activity promoted inclusive, cooperative learning while strengthening students' linguistic, digital, artistic, and scientific competencies. It also enhanced their ability to synthesize information, communicate effectively, and think critically—while fostering a greater appreciation for the value of local historical and environmental heritage. Knowledge, in this sense, becomes the first step toward responsible stewardship: only by understanding the value of our cultural and natural assets can we contribute to their sustainable preservation and promotion. The initiative fully aligns with the Sustainable Development Goals (SDGs) of the 2030 Agenda, particularly:

Goal 4 – Quality Education: by offering an inclusive, engaging learning experience that fosters critical thinking and lifelong learning;

Goal 11 – Sustainable Cities and Communities: by raising awareness of the importance of protecting cultural and natural heritage;

Goal 13 – Climate Action: through reflection on the long-term relationship between humans and the environment and the need to preserve biodiversity;

Goal 17 – Partnerships for the Goals: by encouraging collaboration among schools, cultural institutions, local communities, and other stakeholders.

The visit to Lamalunga, combined with the students' creative outputs, stands as a model of interdisciplinary education—where the memory of the past becomes a foundation for building the future and empowering young people to take on active, responsible roles in society and the wider world.

Deep Time - Educational and interactive activities for schools

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Keywords: deeptime, communication, education.

This work presents the second phase of The Time Machine Project – a travel into Deep Time, a broader initiative dedicated to exploring geological time. The first phase emphasised the potential of palaeoart as an effective, accessible, and cross-disciplinary visual communication tool to make reconstructions of the past more tangible and engaging for a wide audience. Building on that foundation, the second phase, described here, focused specifically on high school students.

By approaching the concept of "time" from multiple disciplinary perspectives, this phase aimed to help students grasp the vastness of geological time and understand the profound transformations Earth has undergone over billions of years. Conducted at the Liceo Scientifico Bertolucci in Parma, the project emphasized the immense durations that characterize our planet's history and illustrated key geological dynamics, major transitions, and global events that have reshaped the Earth's surface, atmosphere, and oceans.

Interactive lessons introduced students to methods of measuring geological time and its division into eons, eras, periods, and epochs, highlighting the vast differences in their durations. The crucial role of fossils as indicators of biological change and tools for dating rocks was also explored, enabling the reconstruction of relative timelines of Earth's history. Students actively participated in constructing a large-scale timeline to visualise geological time and key transformations of the Earth system. Through this hands-on activity and other educational tools, they were able to quantify the immensity of deep time and understand how slow, gradual processes as well as sudden, catastrophic events have shaped the Planet we inhabit today.

The marginal role of Earth Science in Italian Natural Science lessons: evidence from student feedback

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Keywords: Earth Science education, students, national guidelines.

The Italian National Guidelines stand out as one of the few curricula that include Earth Science as a required topic in upper secondary schools. Nevertheless, within the broader field of Natural Sciences, Earth Science remains underrepresented compared to Biology and Chemistry, both in terms of curricular emphasis and educational practice (Occhipinti, 2014; Boniello, 2016). This imbalance is also reflected in students' participation in science competitions and their enrolment in earth science university programs.

To investigate the marginal role of Earth Science in Natural Sciences lessons delivered by Italian teachers, we administered a questionnaire to students participating in a didactical experimentation (Gravina & Iannace, 2024a, 2024b). During the 2024/25 academic year, a sample of Italian liceo students was engaged by their teachers in an experimental educational activity aimed at testing an Earth Science curriculum that emphasizes student interest and engagement. Together with their teachers, students completed pre- and post-tests designed to assess their needs, interests, and self-confidence in Earth Science. Special attention was given to their preferences regarding the topics listed in the Italian National Guidelines. Preliminary results suggest that Earth Science is more extensively covered in lower secondary school than in upper secondary education. Furthermore, among the Earth Science topics currently included in the National Guidelines, students showed limited interest in geological content such as plate tectonics, minerals, and rocks. Conversely, they expressed greater enthusiasm for topics like the solar system—topics that are no longer part of the current Natural Science curriculum and are not centered on the Earth as a dynamic system.

These findings offer significant insights for the ongoing revision of the upper secondary school science curriculum. They also raise important questions for educators and researchers in Earth Sciences education, particularly regarding whether students' lack of interest is due to the nature of the topics themselves or the way in which they are taught. Ultimately, the results support the development of educational resources and teaching strategies that aim to foster greater student engagement in Earth Science.

Boniello A. (2016) - Geoscience education using virtual worlds: The Unicam Earth Island project (Doctoral dissertation). University of Camerino, International School of Advanced Studies.

Gravina T. & Iannace A. (2024a) - Revitalizing Earth Science Education in Italian Upper Secondary Schools: Crafting New Educational Materials Aligned with National Guidelines (No. EGU24-7797). Copernicus Meetings.

Gravina T. & Iannace A. (2024b) - From Textbook-Based Instruction to Skills-Enhanced Activities: Transforming Earth Science Education in Italian Upper Secondary Schools. AGU annual meeting, Washington DC 9-13 December 2024.

Occhipinti S. (2014) - Models and guidelines for more effective tools and paths in an active teaching-learning in Earth sciences: Looking for a unifying principle (Doctoral dissertation). University of Camerino, International School of Advanced Studies.

Earth Science Education in Italian High Schools: a Curriculum proposal based on national context and teachers' feedback

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Keywords: Earth science education, curriculum development, national indication.

Earth Science is a mandatory component in several types of Italian high schools, integrated within the broader Natural Sciences curriculum, which also includes Biology and Chemistry (D.P.R. 15/03/2010 n. 89). However, it remains underrepresented compared to Biology and Chemistry, both in terms of curricular focus and the number of instructional hours dedicated to it by teachers. To better understand the current state of Earth Science education in Italy, we conducted a national survey in 2023 involving Natural Science teachers. The results indicated a limited use of laboratory and field-based activities, with a predominant reliance on traditional, lecture-based teaching. Teachers identified limited instructional time as the main barrier to effective teaching (Gravina & Iannace, 2023).

In response, we developed a five-year Earth Science curriculum that reflects the actual number of hours allocated to Natural Sciences and aligns with national guidelines, ensuring a balance, and, whenever possible, an integration, among Biology (particularly at the second year with a laboratorial introduction to evolution and geologic time), Chemistry, and Earth Science topics. The curriculum emphasizes STEM competencies, adopts student-centered learning approaches, and incorporates real scientific data. It includes detailed lesson plans, classroom materials, and assessment rubrics tailored for teachers with diverse academic backgrounds. During the 2024/25 academic year, the curriculum was piloted in selected schools across Italy. In each school, two teachers participated and were supported throughout the year via a dedicated training program. This program provided updated Earth Science content and practical guidance on implementing the proposed lessons and methodologies. We intentionally involved teachers without a geology background to assess whether the proposed materials could effectively support Earth Science instruction in such contexts. Teachers and their students also took part in a pre-/post-evaluation process using validated questionnaires. These tools aimed to collect feedback on the proposed materials and to assess the overall status of Earth Science education in Italy.

The feedback gathered will play a key role in refining the curriculum, which will be published as an open educational resource. It will also contribute valuable insights for the ongoing revision of the national curriculum guidelines for upper secondary school science education.

Gravina T. & Iannace A. (2023) - Earth science teaching in Italian Upper secondary school: the floor to Natural Science teachers. In The Geoscience paradigm: resources, risk and future perspectives. Congresso congiunto SIMP, SGI, SOGEI, AIV, Potenza (Italy), 19-21 Settembre 2023.

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How to evaluate the effects of seminars at secondary school students

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Keywords: Earth Sciences, scientific divulgation, secondary school.

During the PCTO (*Percorsi per le Competenze Trasversali e Orientamento* - Paths for Transversal Skills and Orientation) activities in 2023, 339 students from four secondary schools of Rome participated to four different seminars in two days on Energy transition at Sapienza University of Rome. The arguments treated during the seminars dealt from basic concepts of Physics such as energy, power, thermodynamics, black-body radiation to basic concepts of Chemistry (reactivity of the substances), Economy, Sociology and Earth Sciences. Each seminar lasted two hours and was anticipated by administering a test containing 15 questions with four possible answers. To each positive answer, it was assigned +2 vote, summing to 30 in case of 100% correct answers. Wrong answers were assigned to -1 vote, while no answer was assigned to 0 vote. The time to complete the text was 20 minutes. After the ex-ante evaluation test, the seminar was administered, with a break of 15 minutes after the first hour. At the end of the seminar the same test was presented ex-post to the students. The questions that looked incomprehensible or difficult to answer ex-ante the seminar were then seen with a completely different approach ex-post the seminar.

This contribution presents the results of the tests showing the great increase of positive answers moving from ex-ante to ex-post results. For example, the ex-ante average vote of the first seminar (entitled “Basic facts”) was much lower than the same test administered ex-post the seminar (7.9 vs. 25.5). The ex-ante and ex-post standard deviations are not particularly different (6.4 and 4.8, respectively). Similar results were obtained for ex-ante average vote of the second (“Mental Transition”), third (“Climate and Energy Flux”) and fourth seminar (“Let’s not get too hot, ok?”), which were much lower (8.1, 6.9 and 6.3, respectively) than the ex-post seminars (25.7, 24.1 and 24.5, respectively).

After having completed the ex-post test, a long discussion with the students started, trying to explain where they made errors and focusing on their bias on specific concepts or the complete absence of knowledge or specific processes or effects of instintive choices. The results are presented here with a statistical approach and examples of questions and answers, reporting the main implications emerging from this study. Such approach is considered in a very positive way, because it offers to the relator how and where to improve his/her presentation style, but, above all, it offers to the students a direct proof of their knowledge on specific arguments before and after having participated actively to a seminar. The idea that the students will be evaluated directly after the seminar is a strong invitation to a non-passive perception of the knowledge transfer process.

Human particles: simulating seismic waves, paleomagnetism, and more with kinesthetic earth science models

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Keywords: Earth Science education, kinesthetic models, STEM activity.

In an era where students increasingly rely on artificial intelligence and smartphones, meaningfully engaging them in Earth Science has become more challenging than ever. At the primary and secondary school levels, Earth Science is often perceived as the "Cinderella" of STEM disciplines: its terminology and core concepts are frequently seen by students—and sometimes even by science teachers—as abstract, boring, or irrelevant.

Kinesthetic learning—where students actively engage through physical movement and tactile experiences—offers a powerful counterbalance. By incorporating models and activities that allow students to "feel" and "do" Earth Science concepts, teachers can reignite interest, improve retention, and bridge the gap between abstract concepts and real-world phenomena.

In this context, one of the key roles of the teacher is trying to bring freshness and relevance into the classroom, transforming Earth Science lessons into experiences that are very inclusive, intriguing, and stimulating—in a word, *engaging*.

The present contribution is intended to encourage science teachers to adopt simple kinesthetic models for the purpose of representing geological phenomena. These models involve the use of students' own bodies to simulate particles—sometimes as rocks, minerals, or even single atoms.

In particular, we propose several models designed like playful activities to be performed in an outdoor setting (for example the schoolyard) and guided by precise instructions . The first one simulates P and S seismic waves, both in solids and in liquids (IRIS & Shakealert, 2018). This model assists students in visualising the particle-level behaviour and clearly distinguishing how waves propagate through different states of matter.

Other activities inspired by Earthlearningidea website, include a simulation of residual magnetization in igneous and sedimentary rocks, where students represent magnetite grains acting as magnetic needles. This exercise is particularly effective for senior high school students tackling complex topics such as magnetic field reversals or the migration of magnetic poles-phenomena that are often difficult to conceptualize on a microscopic scale (Atit et. al., 2015).

Finally, the kinesthetic model can be useful to represent the oxygen isotope ratio ($\delta^{18}O/\delta^{16}O$) in order to provide insight into past climate changes, bridging the gap between abstract isotopic data and concrete scientific understanding (Macario, 2014).

Atit K. et al. (2015) - Fostering spatial thinking in geoscience education: An overview of the spatial thinking workbook. Journal of Geoscience Education, 63(2), 134-142, https://doi.org/10.5408/14-09.1.

IRIS & ShakeAlert (2018) - Human Wave: Modeling P and S Waves. At: https://serc.carleton.edu/ANGLE/educational_materials/activities/205293.html.

Macario M. (2014) - Educational resources to teach geosciences in the Italian Schools based on a research case study from ANDRILL AND-1B drill core, Antarctica. (PhD Thesis).

Innovative approach to science education: generative Artificial Intelligence for learning

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Keywords: generative Artificial Intelligence in education, STEM education, interactive learning.

Generative Artificial Intelligence (GAI) is revolutionizing the educational approach in Natural Sciences and Geosciences, providing innovative tools to enhance student engagement and comprehension at all levels.

This paper explores the integration of GAI into teaching, highlighting how advanced language models, conversational bots, and applications can facilitate the creation of personalized and interactive content.

It serves as a valuable resource for educators, enabling them to develop practical and engaging teaching activities, such as the creation of dynamic concept maps that connect complex geological phenomena, the development of interactive quizzes tailored to individual competence levels, collaborative writing of interactive scientific stories in which students can explore future scenarios related to climate change, and the generation of 3*D* models of geological structures using automated generation software.

Additionally, the paper discusses the potential of GAI in formative assessment through personalized feedback and adaptive learning pathways.

Pedagogical and ethical implications of using these technologies are also examined, emphasizing the need to balance digital innovation with traditional educational approaches to ensure meaningful and sustainable learning.

Field educational activity in Caffarella Valley, Rome (Italy): geosciences, sustainability and cultural exchanges

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Keywords: geoheritage, citizen engagement, experiential fieldwork.

In April 2024, a field educational activity was organized to the Caffarella valley in Rome, involving an Italian third-year high school class and Turkish guests (students and a teacher) visiting the school for a cultural Erasmus exchange. The Caffarella Valley, a 200-hectare area located between Via Latina and Via Appia Antica, serves as a remarkable example of how citizen cooperation can contribute to the protection of the territory. Before starting the excursion was made a geological introduction of the area, related to the Vulcano Laziale activity and landscape evolution. This task was supported by educational panels based on drawings installed by the local committee at the Vigna Cardinali information point. Observing the landscape formations and different deposits allowed participants to understand how geology has influenced human activities and also the biosphere. During the visit was introduced and explored the "G20 Green Garden" project, an initiative aimed at raising awareness about climate change and environmental sustainability. Special attention was given to the trees planted in the area by the local community, which represent concrete actions to mitigate the impact of climate change, preserve biodiversity, and improve air quality. Along the route, though simple sensory exercises, it was possible to perceive the temperature difference between humid, shaded areas and those more exposed to the sun. Additionally, was discussed the map of surface temperatures recorded during the summer period 2017-2022 for the investigated area.This experience highlighted the importance of environmental education and community engagement, fostering an informed and responsible citizenship while strengthening cultural ties. Additionally, it underscored the key role of geosciences in understanding the environment we live in. Dissemination: the students created an interactive map to navigate the itinerary and explore the proposed themes.

Exploring climate change and its marine impacts through inquiry-based learning: an experimental study with K8 Students using Minecraft education

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Keywords: climate change, marine ecosystem, Minecraft.

Climate change poses significant threats to marine ecosystems, including glacier melting, sea level rise, and the introduction of alien species—phenomena particularly evident in semi-enclosed seas like the Mediterranean. To foster environmental awareness and scientific literacy among young students, this study engaged 25 K8 students (13-14 years old) in a structured educational pathway designed to explore the causes and consequences of climate change, with a special focus on marine ecosystems (IPCC, 2021). The project aimed to (1) increase students' understanding of climate change and its impact on the marine environment (Poloczanska et al., 2013), (2) raise awareness of issues such as sea level rise and alien species invasions (Öztürk, 2021), (3) introduce climate mitigation strategies like offshore wind farms, (4) enhance research and digital literacy through guided web inquiry, and (5) promote collaborative and creative learning via 3D digital platforms and inquiry-based learning.

Over a period of two months (approximately 20 hours), students participated in four sequential phases: (1) a thematic introduction by researchers from the National Research Council (CNR) about climate change in general and its impact on marine ecosystem; (2) web-based research on how marine ecosystems react to climate change; (3) the construction of interactive educational scenarios using Minecraft Education to visualize their findings; and (4) assessment via a structured online test. The Minecraft scenarios reflected key climate-related phenomena such as glacier melting, rising sea levels, the spread of non-native marine species, and the role of renewable energy sources in mitigation efforts.

The final evaluation revealed high student engagement, strong participation, and solid knowledge acquisition, as evidenced by test scores and teacher observations. These outcomes indicate that integrating scientific inquiry with immersive digital platforms like Minecraft Education can effectively support climate education and environmental responsibility among middle school students (Panja & Berge, 2021).

IPCC (2021) - Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report, https://www.ipcc.ch/report/ar6/wg1/.

Öztürk B. (2021) - Non-indigenous species in the Mediterranean and the Black Sea. Studies and Reviews, 87 (General Fisheries Commission for the Mediterranean). Rome, FAO, https://doi.org/10.4060/cb5949en.

Panja V. & Berge J. (2021) - Minecraft Education Edition's Ability to Create an Effective and Engaging Learning Experience. Journal of Student Research, 10(2), https://doi.org/10.47611/jsrhs.v10i2.1697.

Poloczanska E.S. et al. (2013) - Global imprint of climate change on marine life. Nature Climate Change, 3(10), 919-925, https://doi.org/10.1038/nclimate1958.

Rethinking Earth Sciences communication: from disciplinary fragmentation to an integrated systemic vision (book presentation)

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Keywords: crossdisciplinary integration, technological innovation, environmental complexity.

This book, available in both Italian and English editions, compiles contributions written over the years on this theme, including those presented in this conference session and previous editions, offering a transformative global perspective on Earth Sciences communication and education. It addresses how Earth Sciences, despite their critical relevance to climate change, natural hazards, and environmental sustainability, remain marginalized in educational curricula and public discourse due to their fragmented presentation.

The volume proposes a shift from traditional compartmentalized approaches toward an integrated systems view that reveals the interconnectedness of Earth's processes. The authors explore innovative methodologies that present Earth Sciences not as isolated studies of rocks, minerals, and catastrophic events, but as a coherent framework for understanding our dynamic planet.

The book begins by examining the epistemological foundations of Earth Sciences, highlighting their unique nature and the need for specialized pedagogical approaches that transcend traditional experimental methods. It continues with an exploration of the unexpected connections between geological phenomena and human history, art, economy, and culture, revealing how Earth's processes have shaped civilization in ways often overlooked in conventional education.

Several chapters focus on innovative teaching tools and approaches, demonstrating how simple yet effective learning objects can promote understanding of complex global dynamics when properly contextualized. The book also addresses the challenge of risk communication, offering frameworks to reframe natural hazards discourse from catastrophism to a more nuanced systemic understanding that empowers rather than frightens.

The integration of digital and traditional resources receives particular attention, with contributors sharing insights on balancing technological tools with hands-on experiences to develop diverse competencies. The final sections explore how Earth Sciences can build interdisciplinary bridges, connecting with other fields to address complex environmental challenges and foster the holistic thinking necessary for sustainable development.

Through case studies, educational frameworks, and practical examples, this book offers educators, communicators, and policymakers strategies to transform the perception of Earth Sciences from a "science of rocks and catastrophes" into a vibrant, engaging field essential for developing the interdisciplinary perspective necessary to address our planet's most pressing challenges.

"Nudge": reducing natural disaster risks through education

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Keywords: nudge, preparedness, natural risk reduction.

Influencing behaviour is central to public policy to foster risk reduction, empowering communities to mitigate the impacts of disasters and building a more resilient society. To improve preparedness and awareness to be less vulnerable to increasingly extreme natural phenomena (floods, landslides, earthquakes and tsunamis…), we applied the "nudge" approach.

The "gentle push" is based on the theory introduced in 2008 by R.H. Thaler (Nobel Prize - behavioural economics in 2017) and C.R. Sunstein to influence decision-making processes in everyone's best interest, according to the concept "if I know your thoughts, I can move your choice".

Educational strategies based on "changing contexts" (we make decisions and respond to cues) have the potential to bring about significant changes in behaviour, developing *Safe Skills*.

In the framework of Istituto Nazionale di Geofisica and Vulcanologia (INGV) activities on natural risk reduction, the gentle influence uses *gamification* in *Challenge Based Learning* didactic-collaborative approach for schools of different orders, playing both for challenge between single players by devices (smartphones, tablets) or between classrooms by digital boards. The aim is to lead to low cost way of acting by using instinctive reactions to automatically enable the correct behaviour in case of danger.

The *Salvina's adventures* (Piangiamore & Maramai, 2022), a series of educational games to properly face different dangerous situations related to the occurrence of natural phenomena, inspired the INGV game-based nudge. In particular, the *Salvina and the Flood*, *Salvina and the Environment*, and *Salvina and the 4Rs* games were the starting point to reflect on the importance of knowing our own territory to adopt safe behaviour for water-related disaster risk reduction and for the sustainable use of water through small daily actions. To get the *Transformative Learning* purpose, an emotional video, images and the support of a glossary to enhance learning through educational play, has been used to create the *Acqua Viva (Alive Water)* nudge to participate to the *EPALE (Electronic Platform for Adult Learning in Europe) EDU HACK 2022*. The team "Smart citizens" from the Provincial Center for Adult Education (CPIA) of la Spezia and the INGV researcher won the special "Social award" as the most voted nudge by the Facebook audience and placed fourth in the hackathon (Piangiamore et al., 2023). Another INGV nudge, was designed in the frame of *FCR (Responsible Future Citizens) 2.0* project: *CON.I.RI. (CONvivere con I RIschi naturali. Living with natural risk) - Educational training on seismic and hydrogeological risk.* This nudge acts at school through meetings with researcher and *game learning* activities in presence (*Risk Detective* role table game) and remotely (simultaneous online races between classes). It won the second prize and a special mention at the 'Educational Processes and Projects' Section of the *Basile Prize 2025 - XXIII Edition*.

Thaler R.H. & Sunstein C.R. (2021) - Nudge. Yale University Press, 2021.

Piangiamore G.L. & Maramai A. (2022) - Gaming and Resilience: Teaching by Playing Together — Online Educational Competition at School during the Pandemic. Applied Science, 12(23), https://doi.org/10.3390/app122311931.

Piangiamore G.L. et al. (2023) - Acqua Viva (Alive Water): the Smart Citizens' Nudge" to act on behaviours to water-related Disaster Risk Reduction" book of abstract del WLF6 - 6th World Landslide Forum, Firenze 14-17/11/2023, https://riskdetective.wordpress.com/cose-risk-detective/.

The rocks of Bologna witnesses of the climate past and present

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Keywords: climate change, past.

The geological history of Bologna provides valuable insights into the environmental and climatic transformations that have occurred over millions of years. In this project, we investigated how different types of rocks found in the Bologna area can reveal information about the Earth's past conditions, particularly focusing on the transition from marine environments to continental settings.

Our study highlights how the region once belonged to the area called "Paleo-Romagna," a landscape submerged by the sea that was home to marine organisms such as ammonites. The progressive uplift of the Apennines led to the retreat of the sea and the development of alluvial plains. We analyzed rocks such as the red marble of Verona, originally formed in deep marine environments, and the gypsum of Bologna, which testifies a warm, humid subtropical climate influenced by the Messinian Salinity Crisis.

By examining these rocks, we reconstructed the past climatic conditions, including higher CO_2 levels, different continental positions, and natural climate cycles. Our poster illustrates how geology helps us to understand the deep-time climate history and connects it to current environmental issues.

In our poster we show images of the signs that history has left in the city of Bologna and explain why these marks exist.

In the first image we show an ammonite present in the base of the God Neptune's fountain and it is there because as we said before, the area from which the rock was taken was a marine seabed.

In the second image we see a detail of the gypsum, which has been scratched by frequent rainfall and other events.

What do high school students think about geologists' work?

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Keywords: high-school, geoscience, PLS.

In Italian high schools "science" is taught at various levels depending on the type of curricula. However, even in schools with the applied sciences option, which offers up to five hours of science a week, geology — and Earth Sciences more broadly — is often underrepresented, with greater emphasis placed on biology and chemistry. While science teachers acknowledge the importance of a sound geoscience education, they also tell us that students often have a vague idea about what geologists do. This lack of knowledge about geology and geologists translates into poor student recruitment at degree level, as already argued in a UK case study (Rogers et al., 2024).

At the beginning of several outreach activities conducted in different school types, as part of the "Piano Lauree Scientifiche" (PLS) program, we asked students of the third and fourth high school year what they thought a geologist does. Most responded with references to studying rocks, stones, or minerals, despite having already covered Earth Science topics in their curricula. This perception may reflect a bias due to the academic background of the facilitators, but it could also result from the limited scope of Earth Sciences education, which tends to focus solely on those topics. Notably, despite recent environmental disasters, there were very few mentions about geological risks in the students' responses.

In collaboration with these schools, mostly scientific high schools and a few vocational high schools, we carried out a series of activities aimed at introducing geological topics that are often absent from textbooks, including urban geohazards in Bologna, sedimentary sequences as recorder of past climate changes , micropaleontology, geophysics, meteorites, and landslides. All the activities comprise a field experience. Post-activity questionnaires revealed a consistent trend: student interest in geology significantly increased, particularly when hands-on, participatory activities were involved. This increase in engagement was independent of the instructor's role (students, phd's, post-doc, or professor) and unrelated to the specific content covered.

The qualitative observation of the students during the local PLS program indicates that activities aimed at recognize and classify natural objects (rocks; landslides) are the less appreciated compared to activities that involve technological devices as, for example, drones or seismometers. How to sustain this moment of increased interest remains, however, a challenge.

Rogers S.L. et al. (2024) - "you just look at rocks, and have beards" Perceptions of Geology From the United Kingdom: A Qualitative Analysis From an Online Survey. Earth Sci. Syst. Soc., 4, 10078, https://doi.org.10.3389/esss.2024.10078.

Educational geological map of the sheet n. 374 - Rome (CARG project)

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Keywords: CARG project, educative geology, sheet 374 - Rome.

Despite the growing interest in environmental issues, in Italy geology is a discipline handled mostly by experts, implying that there is still little awareness of the impact of geology in everyday life. Georesources - both commonly used (like clays used for sanitary wares or lavas making up the "sanpietrini" covering the floor of Saint Peter's Square), or occasionally observed (like the "Lapis Tiburtinus", the travertine used to build the Colosseum) - are rarely observed as materials strictly connected with the geological environment where they formed. Additionally, the knowledge on the different types of geo-hazards affecting the territory in which we live is scarce.

The restart of the Geological Cartography project (CARG) in 2020, besides resuming the official surveying and mapping activities at the 1:50,000 scale (D'Ambrogi et al., 2024), allows us to realize a product that aims to bring geological knowledge to a wider audience. Students, but also citizens, tourists, policy makers and stakeholders, will be able to better appreciate the geology of the city of Rome through a digital product containing: i) a simplified geological map of the CARG sheet n. 374 - Rome (Servizio Geologico d'Italia, 2008); ii) a table illustrating the main georesources and geohazards; iii) a synthetic geological profile. By consulting this prototype product, possibly replicable in other cities and areas, people will be able to find information, increase their knowledge, and explore the link between geology and every-day life, geology and cultural heritage, geology and natural hazards, increasing the general awareness on the importance of both preserving the territory in which we live, work and move, and of geology as a discipline.

D'Ambrogi C. et al. (2024) - Progetto CARG: la cartografia geologica verso il futuro. Geologicamente, 13, ISSN: 2705-0149, https://doi.org/10.3301/GM.2023.03.

Servizio Geologico d'Italia (2008) - Carta Geologica d'Italia alla scala 1:50.000, F. 374 Roma. ISPRA, Roma.

Quick and easy hands-on activities to make geoscience education accessible for all: a taste of *Earthlearningideas* proposed by EGU (European Geosciences Union) teacher training workshops

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Keywords: Earthleaningidea, hands-on activities, teacher training.

Teaching Earth sciences topics may be challenging for teachers lacking specific academic background in geosciences or geosciences education, who may rely mostly on written materials and traditional transmissive teaching.

In addition, geosciences address phenomena that are not always accessible first-hand: too big, too slow, too far away, sometimes dangerous.

Earthlearningidea workshops help to overcome these criticalities through hands-on activities that are:

- linked to the curriculum of different school grades
- taking limited time (within 1 "hour" of class time)
- requiring low-cost equipment that can be made with common-use materials
- validated through extensive teaching experimentation

Earthlearningidea worksheets also provide teachers with pedagogical guidance following the constructivist CASE (Cognitive Acceleration through Science Education) approach (Adey, 1999).

In this conference we are presenting some quick and easy hands-on activities addressing different geosciences topics. The related *Earthlearningidea* worksheets, as many others (nearly 100!), are available in Italian, with validated translation by the UNICAMearth group of the University of Camerino (Realdon et al., 2024).

All worksheets are freely downloadable under Creative Commons License from www.earthlearningidea.com

Adey P.S. (1999) - The science of thinking, and science for thinking: a description of cognitive acceleration through science education (CASE). UNESCO- IBE International Bureau of Education, Geneve, https://unesdoc.unesco.org/ark:/48223/pf0000124789

Realdon G. et al. (2024) - Professional development of teachers across the COVID-19 pandemic: the EGU Geoscience Education Field Officer Programme in Italy. Rend. Online Soc. Geol. It., 62, 2-7, https://doi.org/10.3301/ROL.2024.01.

Five years of EGU Geoscience Education Field Officer (GEFO) programme In Italy: an assessment of its impact

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Keywords: geosciences teachers' training, EGU-European Geoscience Union, geoscience education field officer (GEFO) programme.

Addressing the need to improve the teaching of geosciences in Europe and beyond, the European Geoscience Union (EGU), launched the Geosciences Information for Teachers (GIFT) programme in 2003.

This programme was eventually enlarged to reach a wider audience with the appointment of the first Geoscience Education Field Officers (GEFOs) in 2019, with the task of running practical geoscience workshops for teachers in four European countries (including Italy). More GEFOs were enrolled in the successive years in Europe and in non-European countries.

GEFO workshops are offered free of charge to schools, universities, and associations willing to organize professional development activities for teachers lacking specific academic background in geosciences. These workshops propose an innovative way to address geoscience topics included in school curricula, based on CASE methodology (Adey, 1999) and Earthlearningidea resources. The outcomes of the workshops are monitored through an evaluation questionnaire.

The Italian GEFO (G. Realdon) started her activity in 2019 and, after the stop due to the pandemic, has been running teachers' workshop across the country since then.

In this conference we are presenting an assessment of five years of GEFO's activity in Italy, based on the data collected from the workshops' participants.

Between 2019 and 2024, 37 workshops with 562 participants have been run in 12 regions of the country.

Most of the teachers were women, 78.3% were confirmed teachers and more than half had been teaching for 7-25 years. Lower secondary, primary, and upper secondary school teachers accounted respectively for 36 %, 27.2% and 23.7%.

Teachers' appreciation of the workshop was assessed through three 5-point Likert scale questions.

A question about teachers' interest in the workshops, another about their professional interest and a third one about their interest in attending other workshops obtained a mean score of 4.82, 4.72 and 4.75 respectively.

Finally, teachers were asked for comments and suggestions for future workshops. These open answers were analysed through deductive content analysis (Bengtsson, 2016).

Of the 396 collected comments, 31.6% expressed general appreciation for the workshop and the trainer, 26% praised the practical aspects, and 20.7% the theoretical/pedagogical knowledge provided by the workshop. The suggestions from the teachers were 95, 36.8% of which proposing to address other topics or subjects, 26.3% providing methodological/organizational recommendations and 38.4% asking for more/longer workshops or expressing general approval. Following the success of the GEFO program in Italy, EGU has decided to continue funding it.

Nevertheless, still a large proportion of Italian natural sciences teachers do not receive proper academic or in-service training in the geosciences: only the Ministry of Education, with a national initiative, could reach all teachers who need it and - through them - future Italian citizens.

Adey P.S. (1999) - The science of thinking, and science for thinking: a description of cognitive acceleration through science education (CASE). UNESCO- IBE International Bureau of Education, Geneve, https://unesdoc.unesco.org/ark:/48223/pf0000124789.

Bengtsson M. (2016) - How to plan and perform a qualitative study using content analysis. NursingPlusOpen, 2, 8-14, https://doi.org/10.1016/j.npls.2016.01.001.

Fostering sustainability awareness and skills through multidisciplinary educational initiatives

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Keywords: air quality, circular economy, energy restore.

It aims to cultivate transversal skills among high school students, placing emphasis on sustainability and environmental protection through interdisciplinary project-based learning. The main educational objectives include promoting awareness of the environmental impact of daily choices, promoting a shared understanding of sustainability through concrete actions and equipping both students and teachers with the knowledge, skills and attitudes necessary to promote sustainable lifestyles, work and decision-making processes.

The initiative involves a collaboration with the main stakeholders, including the University of Pavia, CONAI, the Municipality of Pavia, Legambiente, Fridays for Future, Rete provincial scuole sostenibili, Rescue SOS Pavia (rete scuole sostenibili del commune di Pavia). The project is developed over the first three years of secondary school (14-16 age). In particular:

First year: students focus on the assessment of the ecological footprint through the measurement of CO_2 emissions and the analysis of fossil fuel consumption, using citizen science methodologies. ◦

Second year: students explore energy consumption patterns, potential environmental impacts and delve into the role of medicinal plants in local culture through hands-on activities and field trips.

Third year: students delve into geosciences, with a specific focus on advanced methods for the characterization of minerals and materials through SEM, RAMAN and X-ray crystallography, combined with application-based learning experiences in circular economy practices.

Furthermore, the program includes CLIL (Content and Language Integrated Learning) activities, including the development of an app for waste recognition, and culminates in the presentation of the results to community stakeholders. This multifaceted approach not only enriches scientific knowledge, but also promotes lifelong learning, sustainability awareness and active civic engagement.

Evaluating dual learning activities to promote awareness on human impacts and climate change

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Keywords: glaciers, environmental footprint, Geographic Information Systems (GIS).

As part of public engagement activities targeting secondary school students, in 2024/2025 we organized a series of dual training (learning and working) projects (PCTO – Percorsi per le Competenze Trasversali e per l'Orientamento) aimed at fostering interest in geosciences, enhancing technical skills, and raising awareness of the environmental impacts of human activities and climate change. Compared to previous editions (Diolaiuti et al., 2024), this year's program introduced two new web applications developed by project researchers: one for estimating individual carbon footprint (Senese et al., 2024) and one for assessing the ecological footprint (carbon and plastic) of fast fashion.

The initiative involved three schools in Milan, Bergamo, and their provinces, reaching around 180 students. The program combined lectures with interactive elements (videos, web apps, and educational games) and hands-on laboratory activities. During labs, students worked with satellite imagery and orthophotos using GIS platforms, particularly the Geoportale of Lombardy. Training topics included i) glaciers (definition, global distribution, inventories, monitoring methods, and climate change impacts) as indicators of climate change, ii) causes of climate change (greenhouse effect, atmospheric composition, rising GHG concentrations), and iii) individual mitigation strategies. A dedicated section explored the environmental impacts of fast fashion, highlighting its significant ecological footprint—especially from e-commerce—and discussing mitigation strategies.

To assess the program's effectiveness, a final questionnaire was administered to all participants, evaluating satisfaction and perceived educational value. Results showed that hands-on activities were most appreciated: 75% of students rated the "immersive experience" session as extremely or very interesting, and 70% did so for the "geoportal" session. In contrast, theoretical sessions were slightly less engaging (only 39% rated the "Glacier, only theory" session as highly interesting). Notably, the fast fashion and carbon footprint topics were the most effective in prompting students to reflect on their personal environmental impact and consider lifestyle changes.

Overall, the project successfully engaged students in geoscience and climate issues. However, the findings highlight the value of interactive, practical sessions. Future editions will increase the focus on hands-on workshops to deepen engagement and foster more meaningful learning experiences.

Diolaiuti G.A. et al. (2024) - Increase students' knowledge of climate change impacts on the environment through dual (learning and working) training projects. Rend. Online Soc. Geol.It., 62, 45-51, https://doi.org/10.3301/ROL.2024.09.

Senese A. et al. (2024) - A user-friendly tool to increase awareness about impacts of human daily life activities on carbon footprint. Sustainability, 16(5), 1976.

Educating for climate sustainability: a twinning project between Italy and Turkey to engage youth and local authorities

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Keywords: climate change, glacier, carbon footprint.

Educating younger generations in sustainability and climate change mitigation is a pressing challenge. Schools and environmental organizations implement diverse strategies, often differing across European countries. To harmonize these efforts, the European Union (EU) has promoted international town twinning projects to foster shared approaches to climate communication and citizen engagement. These projects require participating countries and cities to define common strategies for effectively disseminating climate-related knowledge and to establish mechanisms for evaluating outcomes.

Among such initiatives is the Italy–Turkey Town Twinning project, funded by the EU and implemented over one year by the Municipality of Cinisello Balsamo (Italy, project lead), in collaboration with the Municipality of Edremit (Turkey), the University of Milan, and the Legambiente Innovation Foundation.

This paper presents the strategies adopted and results achieved, with a focus on the replicability and exportability of the methods employed. The project aimed to:

- Improve young people's knowledge of environmental issues, particularly EU climate policies;
- Increase youth participation at the local level, encouraging new initiatives addressing community climate impacts;
- Raise awareness of environmental sustainability among municipal authorities in both countries.

Key activities included:

- Kick-off and regular coordination meetings between Italian and Turkish partners;
- Two cycles of seminars for high school students (grades 4–5) in both countries, covering: i) the physical basis and evidence of climate change, ii) glaciers as indicators of climate change, and iii) possible solutions. These sessions combined theoretical lessons with hands-on activities (e.g., carbon footprint analysis, Senese et al., 2023) and innovative educational tools like immersive experiences (Diolaiuti et al., 2024);
- A public "Summit for Climate and Youth Participation" held in Cinisello Balsamo, mirrored by a similar event in Edremit;
- An international meeting in Edremit involving all Italian partners and additional municipalities (Çankaya, Kadıköy, Nilüfer) to discuss strategies for communicating climate change to youth;
- A final online event open to Italian and Turkish university students to present project outcomes, launch a digital platform, and explore future directions.

The main outcomes were:

- Establishment of local Climate Youth Councils in both partner countries;
- Creation of an e-book compiling all project materials;
- Development of two online platforms to facilitate updates and idea-sharing by the Youth Councils.
- This experience highlights the value of transnational cooperation in promoting environmental education and provides a scalable model for youth engagement in climate action.

Diolaiuti G.A. et al. (2024) - Increase students' knowledge of climate change impacts on the environment through dual (learning and working) training projects. Rend. Online Soc. Geol.It., 62, 45-51, https://doi.org/10.3301/ROL.2024.09.

Senese A. et al. (2024) - A user-friendly tool to increase awareness about impacts of human daily life activities on carbon footprint. Sustainability, 16(5), 1976.

Enhancing geoscience education through orogenesis and rock studies: a peer-tutoring approach in the Dolomites

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Geoscience plays a pivotal role in addressing critical contemporary challenges, including sustainable energy transition, climate change understanding and mitigation, environmental impact assessment of industrial development, water resource management, mineral resource exploitation, and natural hazard management. However, the current curriculum of the Italian "Liceo Scientifico ordinamentale" offers limited coverage of geological topics, primarily focusing on biology and chemistry (Roca & Garcia-Valles, 2020). This project addresses this gap by focusing on Italian orogenesis, specifically within the tectonically active Dolomites, to explore broader Earth science concepts, including orogenesis and petrology. Recognizing the need for research-based and inclusive pedagogical approaches, particularly for students with special educational needs, this project employed a peer-tutoring model, pairing high school (HS) students as tutors with primary school (PS) students as tutees (Topping et al., 2004; Xu et al., 2008). The project had two primary objectives: first, to provide HS students with a robust understanding of the causes, composition, and structure of the Dolomites within their regional tectonic framework; and second, to develop their ability to effectively communicate complex orogenic and petrological concepts to younger learners. Initially, HS students received expert instruction from a geologist, covering Earth's internal structure, the processes of orogenesis in the Italian Eastern Alps, and sedimentary rock identification. This theoretical work was followed by a trekking expedition in the Dolomites Bellunesi, a natural laboratory offering a firsthand opportunity to observe the interplay of tectonic forces, sedimentary processes, and glacial sculpting that has shaped this remarkable landscape. Under the guidance of experienced naturalistic expert guides, HS students examined the sedimentary strata of Monte Avena and Valle dell'Ardo. These strata, originally deposited as horizontal layers in ancient marine environments, exhibit warping and uplift, displaying varied sedimentary rock formations representing distinct depositional environments from the Triassic and Jurassic periods. These activities provided direct experiential learning regarding the materials and processes that have shaped the Dolomites landscapes and reflect broader tectonic forces.Subsequently, HS students collaborated with PS students to deliver age-appropriate lessons. The HS students designed and implemented creative, hands-on activities, including games focused on the formation of the Dolomites, the identification of igneous, sedimentary, and metamorphic rocks, and ancient fossilized remains within sedimentary rocks in prominent monuments of Parma (Urban Geological Exploration). Throughout the project, HS students were actively engaged in their own learning and received ongoing feedback. The project not only enhanced HS students' knowledge of Dolomites orogenesis, including glacial erosion and associated lithologies, but also cultivated essential teamwork skills through the completion of practical tasks. The integration of formal instruction, immersive field experiences, and peer tutoring created an inclusive learning environment that leveraged diverse student abilities, making Earth science education more accessible and engaging. This project demonstrates a successful model for integrating orogenesis and rock studies into geoscience education through a dynamic and collaborative learning framework.

Roca N. & Garcia-Valles M. (2020) - Trainee Teacher Experience in Geoscience Education: Can We Do Better?. Geoheritage, 12, 92, https://doi.org/10.1007/s12371-020-00518-8.

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