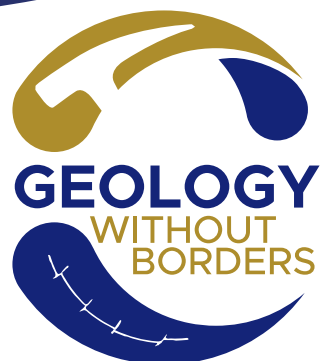




Trieste 14-16 settembre 2021

# ABSTRACT BOOK

a cura della Società Geologica Italiana



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## **PLENARY SESSIONS**

## **The added value of frontier-crossing research projects: a few lessons and opportunities**

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*Keywords:* collaborative research, balance.

Advances in science have been most often achieved by outstanding individual efforts and pioneering work from the ancient times to the 19<sup>th</sup> century, with only few examples of team work. In the geosciences, such collaborations often happened in frame of explorations and the physical need to make teams on a ship or uncommon field conditions on land. Through the decades of the 20<sup>th</sup> century, works undertaken by two or more researchers became more and more common, also independently of fieldwork. In the same time, primarily in the digital era, the quantity and flux of information has started to increase rapidly. This has lead to numerous large collaborative projects in geosciences. In this talk I present a few examples of various types, primarily from the Alpine region and the solid Earth community, with the goal of demonstrating the added value of these projects, and of crossing frontiers in terms of geoscience (sub-)disciplines, spatial and temporal scales, and traditions of cooperation. While these examples show various ways of success, I also discuss some of the potential pitfalls. Overall, I hope that the balance is convincing and triggers other collaborative research projects without borders.

## Geological Things from other Worlds

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*Keywords:* planetary geology, comet 67P, Mercury, Mars, astronauts geological training, planetary geological mapping.

Any planetary exploration goal can only be achieved through an intense collaborative effort among geologists, geophysicists, astronomers, astrophysicists, optical and mechanical engineers. In the last years we have indeed witnessed an exponential increase of space missions to diverse planetary bodies of the Solar System, including in situ robotic and crewed explorations led by different National Space Agencies. This trend is going to further increase in the years to come and is consequently leading to an urgency in a collaborative action in which geological experience will be essential to select adequate payloads and robotic systems, define successful observational strategies of orbital missions, assuring safe landing and fruitful traverses of robotic and human missions, scientifically exploit the retrieved data, store and analyze the returned samples, find key analogue sites and materials, train astronaut crews in field exploration, explore and evaluate in situ resources, identify environments with the potential to preserve astrobiological signatures.

In this framework, planetary geologists should face major science questions and pivotal goals which terrestrial geologists are normally not used to take into consideration. Just to cite some of them: How do the solar nebular and protoplanetary disk evolved? How different bodies of the inner and outer solar system differentiate and geodynamically evolve? What are the origin and role of water and other volatiles on different planetary bodies? How climate variability evolved on different bodies with atmosphere and how does the interaction between surface and exosphere work in atmosphere-less bodies? How can be refined the global stratigraphy of different planetary bodies? How and at which extent gravitational forcing or major hypervelocity impacts induce changes on the tectonic and volcanic evolution of any planetary body? What are the physical ranges within which plate tectonism might have evolved or declined on different bodies? Which are the best sites for stable settlements on Mars and the Moon? Why similar bodies such as Venus and Earth have had so dramatically different evolution in term of greenhouse effect? Which kind of resources might we find on planetary and small bodies, and how we can exploit them?

In this presentation I will illustrate the broad multidisciplinary context of planetary science and space exploration in which geologists are called to give their contribution, focusing on specific examples I have been directly involved in, such as Bepi-Colombo, Rosetta and Exo-Mars ESA missions, the ESA PANGAEA astronaut training on field geology, and the recent European planetary geological map infrastructure GMAP.

## Understanding the Earth System through scientific drilling

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*Keywords:* IODP, subduction zones, seismogenesis.

The world oceans share in the transformations of the Earth in its complex dynamics that connects the solid Earth with life, climate and society. The seafloor therefore preserves an archive that can reveal the interactions that have shaped the Earth over the past two hundred million years, which can help us to decipher the future of our planet. Scientific ocean drilling provides a direct access to this archive. By its own nature, this requires not only a multidisciplinary approach, but often pushes the boundaries of individual Earth science disciplines. The evolution of our knowledge of the Earth gained during the last five decades is closely linked to progress in scientific ocean drilling, and this remains the only tool available to the international community to keep exploring the seafloor. Understanding the connections amongst the biosphere, high-CO<sub>2</sub> climate systems, deep geologic time, and the currently active Earth processes within the solid Earth system is critical to realize society's sustainable development objectives. Key areas for evaluating the dynamics and feedbacks between the interior and the exterior of our planet are subduction zones. There, environmentally-driven changes, modifications of surficial and sedimentary process dynamics, and deep subduction processes can all shape forearc tectonics and influence plate boundary megathrust coupling. Understanding the mechanics of megathrust slip at subduction zones that leads to great earthquakes and tsunamis will allow us to better evaluate and mitigate the future risks of these natural hazards to society. Here I will present some examples of how the study of subduction zone megathrusts requires a comprehensive approach, whereby the mechanics of the megathrust and the geological and surface processes at work can be linked, modelled and quantified.



**S1.**  
**Tectonics and sedimentation**

*CONVENERS AND CHAIRPERSONS*

*Giovanni Barreca (University of Catania)*

*David Iacopini (University of Naples - Federico II)*

*Stefano Zanchetta (University of Milano – Bicocca)*

*Francesca Cifelli (University of Roma - Roma Tre)*

## Structural setting of the Kvarner area (Northern Adriatic)

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*Keywords:* North Adriatic Sea, External Dinarides, structural style, Messinian, lineaments, canyons, clinofolds.

Several studies have described the geological setting of the Kvarner area (Northern Adriatic Sea) based on the outcropping sedimentary sequences. They are mainly represented by the Adriatic carbonate platform (AdCP) affected by the compressional/ transpressional deformation of the External Dinaric orogen, which produced both thin- and thick-skinned tectonics.

In this study, we used an extensive 2D seismic, and well dataset initially acquired for hydrocarbon exploration of the Kvarner area. The 2D seismic lines were calibrated by the wells, which allowed us to reconstruct the connection between the tectonic structures of the offshore and onshore areas. In particular, the continuity of the main SE-Istrian anticlines and the northern Dalmatian Islands has been recognized and depicted by a time structural map of the base of the Plio-Quaternary sequence. These anticlines, originating from the pre-Messinian Dinaric thrust system, were reactivated by the post-Messinian transpressional tectonics, which produced positive flower structures. Between the anticlines, sharp valleys, canyons, and channels crossing the Kvarner offshore area outline two main low structural lineaments. They are partially incised during the Messinian and can be followed in Istria onshore for several kilometers. Messinian and post-Messinian erosional effects were influenced by the morphology of older tectonic structures produced by the Dinaric compressional phase and the more recent transpression. Fluvial-deltaic depositional systems fill the valleys with mainly clinofold geometry. Wells never calibrated this sedimentary sequence. Thus, we hypothesize a Plio-Quaternary or a Late Messinian age, related to the Lago-Mare Formation.

The back-thrusts seem to have been recently reactivated as strike-slip structure in the Rijeka city area and the Krk island (eastern Kvarner). The AdCP shows a gentle tilting toward the Apennine Chain in the western explored area, whose outermost front is situated more than 80 km to the west. This tilting re-activated older normal faults and is probably enhanced by an uplift of the Istria peninsula.

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## **The role of structural inheritance in the structuration of the External Rif fold and thrust belt (Rif belt; Northern Morocco) insights from tectono-thermal modeling**

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*Keywords:* Rif belt, thermal modeling, north African paleomargin, Alpine orogenesis.

The Rif belt (Northern Morocco) represents a key area located at the junction between the Mediterranean domain and the Central Atlantic and forms the western edge of the Alpine orogenic system developed during the convergence between the Africa and Eurasia plates. The Rif belt was built mainly during the Miocene when the regional geodynamics is dominated by the westward translation of the Alboran Domain, leading to the closure of the Maghrebien flysch basin that over-thrust the External domain (i.e. from north to south we recognize, Intrarif, Mesorif and Prerif for different external Rif paleogeographic sub-domains).

The Rif fold and thrust belt shows a lack of cylindricity along strike expressed by the variations of amount and rates of shortening and tectonic transport as well as structural styles. These features are well expressed in the Mesorif (External domain) where the levels of preservation of the original geometry of the north African paleo-passive margin differ from east to west. In the eastern Rif the Jurassic rifting geometry is still preserved (e.g. Senhadja unit, see Gimeno-Vives et al., 2019), while it is completely overprinted by the compressive Alpine deformation, and overlain by syn-orogenic basins (e.g. Zoumi basin). At depth this variation is expressed by varying crust thickness, with a higher value of 46 km in the central Mesorif (Izzarene Upper Jurassic-Cretaceous units) and a shallower one in the eastern Mesorif according to Petit et al. (2015). The Izzarene structure is bordered at surface by two major thrusts marked by Triassic evaporites injected from depth along them. Thus, they probably merge at depth with high-angle deep-rooted faults inverted and inherited by the former architecture of the north African paleo-passive margin.

In order to decipher the role of this complex crustal structure and link it to the shallow structural style and kinematics of Rif External domain derived from the deformation of the rifted north African paleo-margin, we adopted a multidisciplinary approach merging data from commercial seismic lines and wells, with field survey, structural mapping, thermal maturity analysis (vitrinite reflectance, micro-Raman spectroscopy on dispersed organic matter and %I in I/S mixed-layers) and thermo-structural modelling.

## The Strait of Messina: Seismotectonics and the source of the 1908 earthquake

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*Keywords:* Messina-Reggio Calabria earthquake, seismic reflection data, causative fault, seismicity cut-off, stress transfer, 3D modelling.

More than 100 years after the devastating Messina-Reggio Calabria earthquake ( $M=7.1$ ), the largest seismic event ever recorded in southern Europe in the instrumental epoch, its causative seismic source is still unknown, and the several rupture models proposed in the last decades are far from any shared solution. Data interpretation on a new dataset of sub-seafloor geophysical soundings with unprecedented resolution, relocated seismicity, and Vp model, together with morphotectonic investigations and inverse modelling of available levelling data, provide additional constraints on the deformation mechanisms and seismotectonics of the Strait of Messina area. High-resolution seismic lines in the offshore, along with displaced Quaternary marine terraces on land, point to active deformation along a previously unmapped  $\sim 34.5$  km-long extensional fault. The spatial distribution of relocated earthquakes highlighted that a cut-off of the seismicity occurs within the crustal depth. The seismic discontinuity roughly delineates a foreland-dipping and low-angle discontinuity apparently confirming previous studies predicting low-angle seismogenic sources for the 1908 seismic event. However, according to the overburden stress and the attitude of the discontinuity, stress analysis suggests that a seismic slip is unlikely along it. This, therefore, weakens the hypothesis that a large earthquake may have nucleated along a low-angle discontinuity. Rather, aseismic creeping is instead expected since movement is allowed only by assuming a mechanical weakness of the plane. This mechanical behavior is currently also supported by the large interseismic strain-rate recorded in the area. Both seismic tomography and crustal-to-subcrustal scale 3D-modelling strongly suggest a cause-and-effect relationship between slab retreat, mantle wedging, uplift in the upper plate block, and active extension in the Strait of Messina area. Lithospheric doming of the upper plate is here interpreted to be the main process controlling uplift in the Peloritani Mts. of Sicily and subsidence in the Strait of Messina region where deformation is mainly accommodated by the weak low-angle discontinuity. In this frame, an almost aseismical slip toward the foreland of the low-angle discontinuity is here accounted to produce stress perturbation in the area. Coulomb stress change modelling revealed that simulated normal slip on the foreland-dipping discontinuity can induce additional stress and promote failure in the overlying brittle faults. An excellent fit between calculated and observed subsidence is achieved by geodetic data inversion that resolved a normal slip on the low-angle discontinuity and a transtensional (slightly left-lateral) motion on the 34.5 km-long and previously unknown extensional fault. The fault-length along with the observed seafloor displacement make this tectonic structure as the most likely to have produced large earthquakes in the Strait of Messina area.

## Structural inheritance in the Northeastern Mediterranean basin

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*Keywords:* structural inheritance, northeastern Mediterranean Basin, seismic reflection.

The Eastern Mediterranean Sea results from an alternation between extensional and contractional phases. Although several geodynamic reconstructions have been proposed, its tectonostratigraphic evolution is still a matter of debate. The main tectonic phases that affected the area were the Mesozoic rifting, followed by a Cenozoic contractional phase, due to the inception of the convergence between Africa and Eurasia and the subduction of the oceanic lithosphere. From the Miocene, the opening of the Red Sea induced a rotation and northward migration of the Arabian Plate. At the same time, the rollback of the subducting oceanic lithosphere in the Central Mediterranean area favoured a westward escape of the Anatolian plate squeezed out by the northward migration of the Arabian Plate. Our study area is located in the easternmost portion of the Mediterranean Sea, offshore Turkey, Cyprus and Syria, on the ancient passive margin of the Tethys between the Arabian continental lithosphere and the African oceanic lithosphere. Along the Cyprus Arc, the Neo-Tethys oceanic crust is subducting toward NE. Most of the authors (Symeou et al. 2018 and references therein) suggested that this system is continuous from Cyprus to Syria.

In this work, multi-channel seismic reflection profiles have been used to analyze the basement nature (oceanic vs continental), to recognize potential subduction zones and their lateral continuity, and to reconstruct the contractional events. Our data suggest a continental nature of the basement, excluding a continuous ophiolite complex and subduction in eastern Cyprus offshore. Most of the recent structures evidenced in the area derive from transpressional reactivation of inherited extensional fault systems.

Symeou V., Homberg C., Nader F.H., Darnault R., Lecomte J.C. & Papadimitriou N. (2018) - Longitudinal and temporal evolution of the tectonic style along the Cyprus Arc system, assessed through 2-D reflection seismic interpretation. *Tectonics*, 37(1), 30-47.



## The response of the Apula plate to the advancing Calabrian and Hellenic wedges (Northern Ionian Sea): implications for subduction processes and tectono-stratigraphic evolution

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*Keywords:* Northern Ionian Sea, Calabrian Accretionary Wedge, Hellenic Wedge, Apulian foreland, transpressive tectonics.

In the Northern Ionian Sea, the Calabrian Accretionary Wedge (CAW) is facing directly the subducting Apula plate, mainly made of Mesozoic to Tertiary Carbonate Platform (Del Ben et al., 2010; Volpi et al., 2017). This contribution illuminates the structures and stratigraphic relationships between the frontal part of the orogenic belt, the foredeep and adjacent Apulian foreland. A detailed seismic facies analysis of four multichannel seismic profiles has been carried out to define the tectonic-sedimentary evolution of the study area but without exploration wells not available for these deep offshore area. Seismic interpretation allows to identify four main structural domains: the highly tectonized CAW; the narrow foredeep basin filled by a Pliocene-Holocene subhorizontal succession laying above buried normal faults; the massive carbonate succession of the Apulian Platform showing reef and carbonate platform margin facies; the layered succession of the Apulian Platform characterized by “intra-platform” facies in the easternmost portion of the area. Three main regional unconformities with characteristic relationships with structural trends were recognized: i) the Messinian unconformity, related to a regional and significant erosion associated to paleokarst processes on the exposed Mesozoic Apulian Platform, is cut by an array of normal faults in the Apulian foreland and by thrust in the accretionary wedge; ii) the angular and erosive middle Pliocene Unconformity truncates the Lower Pliocene reflectors and is affected by normal faults in the foreland and by compressive tectonics in the CAW; iii) a Jurassic/Cretaceous unconformity in the Apulian foreland is marked by Cretaceous reflectors onlapping the Jurassic carbonate platform. The CAW is characterized by compressive tectonics with several fore-thrusts forming a leading imbricate fan system nearby the orogenic front. The Mesozoic Apulian platform is affected by active extensional tectonics driven by flexural bending since Lower Pliocene (Volpi et al., 2017; Maesano et al., 2020), that probably reactivated old normal faults related to the Permian-Triassic rifting stage. The structural map shows that transpressive and positive inversion tectonics is a common deformational style in the central sector of the foreland, suggesting that the Apulia plate is already part of the Calabrian/Hellenic belt. According to these observations, the compressive tectonics affecting the Apula plate is interpreted as related to shortening processes of both the CAW and Hellenic wedge whose interference plays an important role in defining the tectonic-stratigraphic evolution of the Apula Plate in the Northern Ionian Sea.

Del Ben A., Geletti R. & Mocnik A. (2010) - Relation between recent tectonics and inherited Mesozoic structures of the central-southern Adria plate. *Bollettino di Geofisica Teorica ed Applicata*, 51, n. 2-3, 99-115.

Maesano F.E., Volpi V., Civile D., Basili R., Conti A., Tiberti M.M., Accettella D., Conte R., Zgur F. & Rossi G. (2020) - Active extension in a foreland trapped between two contractional chains: The South Apulia Fault System (SAFS). *Tectonics*, 39, 2020TC006116.

Volpi V., Del Ben A., Civile D. & Zgur F. (2017) - Neogene tectono-sedimentary interaction between the Calabrian Accretionary Wedge and the Apulian Foreland in the northern Ionian. *Marine and Petroleum Geology*, 83, 246-260.

## **Tectono-stratigraphic evolution of Jurassic Tethyan rift basins in the Early Cretaceous: a comparison between the Central Apennines and the Southern Alps**

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*Keywords:* Early Cretaceous faults, PCP/basin systems, Umbria-Marche-Sabina Domain, Trento Plateau, Lombardy Basin.

Evidence for the Early Jurassic Western Tethys rifting is in the Alps and the Apennines. This normal faulting phase dismembered a vast carbonate platform (Calcari Grigi and Calcare Massiccio platform) and produced a complex paleogeographic setting made of intrabasinal morphostructural highs and deeper-water basins (i.e. pelagic carbonate platform or PCP/basin system). Basin-fill pelagites and their geometrical and facies variations highlight this complex architecture. There are growing clues for Early Cretaceous, post-rift, synsedimentary normal faults affecting and displacing the margins of PCP, as in the Umbria-Marche-Sabina Domain and the Trento Plateau-Lombardy Basin. Typical stratigraphic and sedimentological features of this syndepositional tectonic phase include: i) the back-stepping of PCP margins, ii) the deposition of calciclastic bodies, iii) the occurrence of neptunian dykes, and iv) the development of angular unconformities. Geological mapping in the Narni-Amelia Ridge allowed to identify field-evidence for this Cretaceous normal faulting. A polygenic breccia ("Mt. Cosce Breccia") made of clasts of lithologies not younger than the Early Cretaceous, dispersed in a matrix of Maiolica-type facies, rests through an erosional surface on a Jurassic horst-block of Calcare Massiccio. Comparable clastic deposits are embedded in the uppermost part of the Maiolica in hangingwall-basin successions, associated with soft-sediment deformation. Lower Cretaceous pelagites (Maiolica+Marne a Fucoidi) are locally seen onlapping the unroofed Calcare Massiccio, as well as infilling neptunian dykes. Impressive similarities were recognized along the Jurassic western margin (Ballino escarpment) of the Trento Plateau, albeit at a larger scale. Here, a Lower Cretaceous polygenic breccia (Ballino, Pregasio and Prabione breccias) bearing heterometric (up to >20 m across) blocks of Jurassic-Lower Cretaceous deposits referable to the Calcari Grigi Group, the basinal Lombardy Succession and the horst block-top Venetian Succession, occurs. The clasts are dispersed in a Maiolica-type matrix. The breccia rests unconformably on the Calcari Grigi Group and on several Jurassic units of the Lombardy basin-margin succession, and is accompanied by neptunian dykes made of Maiolica facies. Where preserved by Neogene Alpine deformations, Cretaceous normal faults were locally observed, sealed by the calciclastics and the uppermost part of Maiolica. Field-evidence suggests a phase of tectonic instability during the late Early Cretaceous, coeval with the deposition of the uppermost part of Maiolica, affecting PCP-basin systems in both Central Apennines and Southern Alps. Cretaceous faults locally re-activated Jurassic ancestors, locally had a higher angle than Jurassic faults, locally developed as new faults. The result was the displacement and rejuvenation of inherited Early Jurassic escarpments, or the backstepping of PCP-margins producing exhumation of Jurassic structural highs.

## **Solving complex structural geometries using virtual outcrop models: a case study from the frontal sector of the Carso anticline (External Dinarides)**

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*Keywords:* photogrammetry, digital outcrop models, structural geology.

Photogrammetry is becoming the most employed means to generate 3D surface reconstructions of outcrops aka virtual outcrop models (VOMs). So far, VOMs have demonstrated great feasibility for visualization and analysis of outcrops, also constituting essential tools to solve perspective bias and granting access to the study of dangerous or inaccessible rock exposures, and facilitating sharing of results (e.g. Tavani et al. 2014, Hodgetts et al., 2015). Additionally, the ease with which 3D models can be generated, starting from any set of overlapping photographs, and especially employing unmanned aerial vehicles (UAVs, or drones) able to bypass scene occlusion effects common to 3D terrestrial remote sensing techniques, has de facto marked the advent of a digital geology era and the routine use of photogrammetry in support of field geology (Pavlis and Mason, 2017). Here we present the structural study of a large-size outcrop located in the frontal sector of the Carso anticline (External Dinarides). The outcrop exposes Eocene platform carbonates in an abandoned quarry. The quarry, which is 80 m high and 100 wide, represents one of the few large exposures in an area where outcrops are generally scarce and vegetation cover dense. The limited accessibility to the cliff of the quarry prevents extensive direct measurements. By using a DJI Phantom 4 Pro V.2 drone, we acquired geotagged photographs and produced a high-resolution and georeferenced VOM of the outcrop. The VOM permitted detailed structural analysis, and the creation of an orthorectified image of the outcrop along the direction of the fold axis, providing insights on the interpretation of this external sector of the Carso anticline.

Hodgetts D., Seers T., Head W. & Burnham B.S. (2015) - High Performance Visualisation of Multiscale Geological Outcrop Data in Single Software Environment, in 77th EAGE Conference and Exhibition 2015. European Association of Geoscientists & Engineers, 1-5, <https://doi.org/10.3997/2214-4609.201412862>.

Pavlis T.L. & Mason K.A. (2017) - The new world of 3D geologic mapping: GSA Today, 27, 4-10, <https://doi.org/10.1130/GSATG313A.1>.

Tavani S., Granado P., Corradetti A., Girundo M., Iannace A., Arbués P., Muñoz J.A. & Mazzoli S. (2014) - Building a virtual outcrop, extracting geological information from it, and sharing the results in Google Earth via OpenPlot and Photoscan: An example from the Khaviz Anticline (Iran): Computers & Geosciences, 63, 44-53, <https://doi.org/10.1016/j.cageo.2013.10.013>.

## Geometry and kinematics of offshore active faults revealed by an integrated multiscale method

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*Keywords:* active tectonics, Southern Tyrrhenian Sea, Calabrian Arc, slab-tear fault.

Diagnostic morphological features (e.g. rectilinear seafloor scarps) and lateral offsets of the Upper Quaternary deposits are typically used to infer offshore active faults. These structures are not necessarily capable of producing large earthquakes as they could be shallow and formed in response to local stresses. We present a multiscale approach to reconstruct the structural pattern in offshore areas and distinguish between shallow, non-seismogenic, active faults, and deep blind faults, potentially associated with large seismic release. The approach is based on the interpretation of seismic reflection profiles with different resolution/penetration and the quantitative morphometric analysis of multibeam bathymetry. The site chosen for testing the method is the Sant'Eufemia Gulf (south-eastern Tyrrhenian Sea) because it is a natural laboratory to investigate the relationships between regional and local processes associated with a slab tear fault (e.g. Rosenbaum et al., 2008) and crustal structures controlling the Plio-Quaternary tectonic evolution (e.g. Brutto et al., 2016). Data highlights the occurrence of three major tectonic events since the Late Miocene. The first extensional or transtensional phase occurred during the Late Miocene. Since the Early Pliocene, a right-lateral transpressional event caused the positive inversion of deep (> 3 km) tectonic features, and the formation of NE-SW faults in the central part of the gulf. Also, NNE-SSW to NE-SW trending anticlines (e.g. Maida Ridge) developed in the eastern sector. Since the Early Pleistocene (Calabrian), shallow (< 1.5 km) NNE-SSW oriented structures formed in a left-lateral transtensional regime. The results of this work integrated with literature data indicate that the transpressional/transtensional structures developed in an ~E-W oriented principal displacement zone extending from the Sant'Eufemia Gulf to the Ionian offshore. The strike-slip zone likely represents the upper plate response to the development of a slab tear fault. The quantitative morphometric and bathymetric analyses indicate that NNE-SSW to NE-SW trending anticlines were negatively reactivated during the last tectonic phase. We suggest that the deep structure below the Maida Ridge may correspond to the seismogenic source of the large magnitude earthquake that struck the Calabrian region in 1905. The multiscale approach contributes to understanding the tectonic imprint of active faults with different hierarchical order developed in a strike-slip zone orthogonal to the Calabrian Arc.

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## The Buntsandstein of Sardinia (Italy) as keypoint of the Western Tethys paleogeography

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*Keywords:* continental-transitional environments, provenance studies, palaeopalinology, Early - Middle Triassic, Sardinia, W-Tethys.

Sardinia played a key role during the opening of the Western Tethys in late Early-early Middle Triassic times, being located at the intersection of several main paleogeographic plates, and its Buntsandstein successions represent a revealing paleogeographic and sedimentary touchstone. Historical and unedited sedimentological data, detailed petrographic studies, and a review of the palynological assemblages evidence that the various formations of the Sardinian Buntsandstein Group differ noticeably from each other and were deposited in different alluvial to transitional environments related to “Alpine” rifting basins. Moreover, strong compositional differences from NS to EW in the island are also observed. They support a morphotectonic rise separating the diverse depositional basins, possibly related to main European ridges in progressive dismantling. The dominating environmental and/or (micro)climate conditions were different in the various areas, and the sedimentary basins evolved independently and diachronous through time. Moreover, the source areas for the sediments varied from articulated to gentle in morphology and substrate composition. The various stratigraphic units of the Sardinian Buntsandstein cover in the center of the island a progressively more altered, smoothed Variscan basement, locally perhaps mobilized by the incoming extensional early Alpine tectonics.

The paleoenvironmental reconstructions evidence an articulated, rough landscape, close to active structural lines, behind the depositional area of the SW Riu Is Corras Formation. A more elaborated depositional environment gave origin to the SW Punta S’ Arridelli and NW Verrucano Sardo formations, whereas a flat, gentle landscape crossed by alluvial channels was located behind the mudflat of the Central Sardinia Escalaplano Formation. These diverse environments could be related to a gradual transgression over the hardrock and a progressive smoothing in time of the Sardinian Variscan basement. The petrographic study reveals the presence of sandstone and carbonate grains of unknown affinity in every Buntsandstein formational unit, possibly related to a dismantled sedimentary cycle. The palynoassemblages support a late Anisian or Pelsonian-Illyrian for the transgression of the Muschelkalk Sea on the Buntsandstein facies, whereas the bottom of the various formations cannot be dated due to a substantial unconformity. The oldest Triassic palynological assemblages identified in the succession are dated to the Aegean. They do, however, not correspond to the base of the Buntsandstein succession. In general, the palynological assemblages support a rather arid climate during the early Middle Triassic, although locally some more humid conditions are observed.

A comparison with nearby coeval plates of the western, subequatorial area of the Tethys (Western Alps, Corse, Provence) evidences the area’s key role during the opening of the “Alpine” rifting basins.



## The importance of Iberia for the kinematic reconstruction of the Mesozoic Alpine Tethys

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*Keywords:* kinematic reconstruction, Iberia, Alpine Tethys.

Fossil remnants of rifted margins sampled in orogens enable to unravel the nature of rocks, structures and conditions controlling the formation of rifted margins and lithosphere breakup. However, a major problem in orogens is that disconnected remnants of only one margin are preserved, while the conjugate has often been subducted and/or obliterated during convergence. Our understanding of rift processes leading to lithosphere breakup is hampered by the impossibility to direct access to well-preserved examples of conjugate rifted margins fossilized onshore. Here we focus our attention on the Mesozoic Alpine Tethys, bounded by the European and African plates and interleaving crustal blocks such Iberia and Adria. A key point has to be resolved in order to reconstruct conjugate distal margins in the Alpine Tethys paleogeographic setting. Iberia has to be positioned during the Mesozoic taking into account the evolution and opening of the southern North Atlantic and the Bay of Biscay. Here we propose a new Mesozoic kinematic model for Iberia, which is compatible at a first order and large scale with recently published data and interpretations from the North Iberian margin and the Pyrenean domain. We discuss the impact of these results for the kinematic reconstruction of the Alpine Tethys.

### 3D modeling and sequential back-restoration as tools for assessing faults deformation rate in offshore setting and estimation of their seismic potential

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**Keywords:** Hyblean-Malta Escarpment, 3D fault model, seismic potential, fault slip prediction, offshore seismic investigation, restoration.

The NNW-SSE trending Malta Escarpment (MESC) offshore eastern Sicily is accounted to have a significant role in the recent seismotectonic picture of the Western Ionian Basin and the Hyblean foreland domain, where some of the largest and most destructive Mediterranean earthquakes occurred (Boschi et al., 1995; Piatanesi and Tinti, 1998; Bianca et al., 1999; Azzaro and Barbano, 2000; Tinti et al., 2001, 2004; Rovida et al., 2016). Seismic data and bathymetric grids allow to better constrain the recent/active deformation pattern affecting the northern sector of the MESC. Accurate seafloor mapping and seismic profiling point to a 60 km-long, roughly N–S trending and E-dipping extensional faults belt slicing across the Ionian offshore between Catania and Siracusa. The fault belt deformed the seafloor producing up to 60 m-high fault scarps. Near fault sediment pattern and displacement analysis provide constraints on the through-time faults activity and deformation rate. Fault parameters were achieved by 3D modeling and then used to derive expected magnitudes and their reactivation propensity. Moreover, empirical scaling relationships (Wells & Coppersmith, 1994; Leonard, 2010) point to a high seismic potential for the detected fault. This combined analysis pointed out how the longest (~60 km) and most continuous fault could be capable of generating  $M > 7$  seismic events, putting forward strong seismotectonic implications for the adjacent and densely populated Hyblean Plateau. The expected magnitude and the estimated recurrence time interval (470–537 yrs) are compatible with those inferred for large historical earthquakes that occurred in the area. However, by comparing the depicted tectonic pattern with other structural settings concerning passive margin worldwide (e.g., along the Pará-Maranhão Basin in the Brazilian equatorial margin, see Matos, 2000) and considering the occurrence of ductile layers in the sediment section (e.g. evaporites), part of the observed deformations (i.e. the seafloor scarps) should be also charged to large-scale slope instability or generated by accommodation space following salt migration in

response to the overlying sediment load. Accordingly, seafloor deformation could be (partially) the result of this kind of process and this issue should be seriously considered in the seismotectonic analysis. Although our study highlights that classical tools used by marine geologists (i.e. high-resolution seismic data and bathymetric grids) work well in detecting offshore faulting, some other significant faults parameters, which are essential in the seismotectonic analysis (e.g. size parameters and slip rate,), need additional approaches to be achieved. In this view, computer-based 3D modelling can represent a starting point for further elaborations such as stress/strain analysis, back/forward and dislocation modeling, sediment decompaction, etc.

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## **Tectonics and sedimentation interplay in the eastern Tertiary Piedmont Basin (Arquata Scrivia, NW Italy): insights from new seismo-stratigraphic analysis**

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*Keywords:* Tertiary Piedmont Basin, seismic interpretation, tectono-sedimentary interplay.

The Tertiary Piedmont Basin (TPB) is an episutural basin located on top of the junction between the Western Alps and the Northern Apennines. This work combines geological mapping and interpretation of a seismic line provided by Eni S.p.A. aiming at investigating the sedimentary succession of the Arquata Scrivia-Carrosio area, a key sector separating the Alto Monferrato sector to the west from the Borbera-Curone sub-basin to the east.

The seismo-stratigraphic analysis of a 33 km-long SE-NE striking seismic line extending from Carrosio to Alessandria and tied to a well, allowed recognizing seven key stratigraphic surfaces, which define six unconformity-bounded stratigraphic units. These could be tied to the outcrop by identifying component lithostratigraphic units at surface. This work contributes to better understanding of the tectono-sedimentary evolution of this sector of TPB, which can be summarized as follows: during the early Oligocene (Unit 1), coarse-grained deltas (Conglomerati di Savignone and Molare Fms.) established, which passed distally (i.e. to the NE) into turbidites and hyperpycnites (Monastero Fm). Following the swift late Oligocene transgression, these marginal fan deltas were overlapped SE-wards by hemipelagic marlstone, containing isolated channelized turbidites (Unit 2; Gremiasco Fm.). Coarse clastic supply was re-established during the Aquitanian-early Burdigalian, with deposition of confined turbidites, mass transport deposits, and channelized turbidites (Unit 3; Castagnola and Costa Montada Fms). In Unit 4 (Costa Areasa Fm., upper Burdigalian-lower Langhian) a basin plain environment established all over TPB, reflecting an increase of the accommodation space driven by southward tectonic tilting of the basin. A further event of basin inversion is that of the intra-Langhian sea level fall, driven by tectonic uplift to the south and recorded by Unit 5 (upper Langhian-lower Messinian), which comprises a range of shelfal systems (Marne di Cessole, Arenarie di Serravalle and Marne di S. Agata Fossili Fms.) making northward transition into turbidites (Cassinasco Fm.). Lastly, Unit 6 (upper Messinian-Pliocene) encompasses a basal package of conglomerates (Conglomerati di Cassano Spinola Fm.), followed upward by early Pliocene clays (Argille di Lugagnano Fm.), over which the shelf margin prograded depositing the Sabbie d’Asti Fm.

In addition, the analysis of velocity data from four additional wells from other sectors of the TPB allowed defining a P-wave velocity and seismic wave propagation model. Besides the increase of velocity with depth, conglomeratic facies were found to show higher velocities (in the range 3500-4200 m/s at depths between 350 and 2800 m) than arenaceous and pelitic facies (in the range 2000-3370 m/s at depths between 350 and 3500 m below surface). Results will help time-depth conversion of seismic lines detailing the subsurface of TPB, contributing to accurate reconstruction of basin fill architecture.

## **Formation and persistence of extensional internally-drained basins: the case of the Fucino basin (Central Apennines, Italy)**

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*Keywords:* Fucino Basin, sediment loading.

The interaction between sedimentation/erosion and faulting represents one of the most intriguing topics in landscape and tectonics evolution. Only few studies have been able to document the feedback between faulting and sedimentary loading from field observations. Here, we focus on how sediment loading/unloading influences the dynamics of fault systems in the Fucino Basin in the Central Apennines (Italy). The Fucino Basin represents a remarkable case study with respect to the other main extensional basins in the Apennines, because of its large dimension, square shape, significant sediment thickness and, its endorheic nature throughout its evolution.

We present a detailed structural and geomorphologic analysis of the Fucino Basin and its surroundings, investigating the kinematic and geometry of each main fault strand. The slickenlines analysis reveals multiple families of slip-vectors and timing of activity, suggesting a change in extension slip-direction from N240° to N200° during middle Pleistocene. Using a local isostatic model, we estimate that up to the 30% of the vertical geological displacement of the faults, which overall ranges from 0.5 to 2.5 km, is related to the sediment loading/unloading. We demonstrate a positive feedback between sedimentation and faulting which may also lead to a re-organization in fault kinematics related to a significant increase in vertical stress. We propose a conceptual model for the permanent endorheic configuration of the Fucino Basin, which includes the effect of sediment loading.

## Evidence of syndepositional tectonics during the Early Permian in the Orobic Basin (central Southern Alps, N Italy)

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*Keywords:* Permian tectonics, synsedimentary deformation, low-angle normal fault system.

Proofs of synsedimentary tectonics during the Early Permian in the central Southern Alps (cSA, N Italy) are recorded in the volcanic and terrigenous successions of the Laghi Gemelli Group, which are characterized by the occurrence of abrupt facies variations often associated with coarse-grained deposits. These features are generally attributed to syn-sedimentary tectonic activity demonstrated by the local occurrence of sediments deformation (Berra et al., 2011) such as liquefaction or slumping due to seismic shaking. Detailed fieldwork allowed us to recognize dewatering structures and sedimentary dikes, ball and pillars and small slumps, occurring along hundreds of mesoscopic faults showing meter-scale displacement in correspondence of high-angle conjugate systems as well as domino-style faults, often accompanied by growth structures. These structures are mainly concentrated in the fine-grained sediments of the Pizzo del Diavolo Formation, which were deposited on top of the volcanoclastic succession of the Ca' Bianca Volcanite and crossed by seismogenic synsedimentary faults.

The Permian synsedimentary structures of cSA are mostly associated with high-angle Andersonian normal faults which are combined with low-angle normal faults (LANFs) that developed along the interface between the Permian sedimentary cover and the Variscan basement (Zanchi et al., 2019). This LANFs system is relevant for the Permian hydrothermal circulation, resulting in widespread tourmalinites deposition along fault zones, and locally in U mineralization. According to our structural analysis the Permian tectonic setting is characterized by pure extension, dominated by ENE-WSW striking normal faults inverted during the Alpine shortening as high-angle reverse faults (Zanchetta et al., 2015).

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## Paleosurface mapping and Quaternary uplift evolution of the Aterno and Tirino Basins

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*Keywords:* Central Apennine, uplift, paleosurface, river inversion.

The Quaternary marks a time of important change in the tectonic regime that affected the central Apennine chain. The shift from the late Miocene-early Pliocene compressional regime to the late Pliocene-early Pleistocene extensional regime produced surface uplift of the chain, tectonic activity expressed along normal faults, and rapid evolution of the intra-montane basins. The development of several paleosurface levels in the central Apennines suggests the uplift was not constant through time; dating those paleosurfaces is critical for determining how uplift rates and landscapes changed through time. The Aterno and Tirino basins preserve a record of subplanar highlands that can be related to paleosurfaces. Recent studies on the Quaternary deposits in the L'Aquila Basin allowed the identification of the Valle Daria abandonment surface, which marks an important phase of base-level fall of the drainage system that occurred during the early Pleistocene (Gelasian). Although morphostratigraphic analysis well describes the evolution of these two basins during the Quaternary, the knowledge related to the higher paleosurfaces and their meaning in the landscape evolution is still poorly constrained. In this study, we applied advanced morphometric and morphostructural analysis to the Aterno and Tirino basins, with a focus on the identification of the main paleosurfaces, their dating, and reconstructions of the baselevel-fall variations of the drainage system through time. We used a 10-m resolution DEM to map the position and elevation ranges of the flat surfaces, extract the drainage system, and identify knickpoints and low-gradient levels. We then combined the morphometric results with the morphostratigraphy and tectonics of the area to define the paleosurfaces, correlate the levels, and assign them ages. We identified 4 main levels of paleosurfaces, the lowermost (P3 and P4) respectively related to Valle Daria (early Pleistocene, top Gelasian) and the top of Fosso Genzano Synthem (middle Pleistocene), the higher ones (P1 and P2) that have been related to the thrust-top basins of Monte Coppe (latest Messinian) and Rigopiano (late Zanclean). We finally applied linear inversion of the Aterno and Tirino drainage systems to infer the evolution of base-level and find a possible correlation with central Apennine uplift phases. Our results show three main events in the drainage baselevel-fall rate. The first two events occurred at ca. 3 Ma and 2 Ma, in accordance with the uplift and abandonment of P2 and P3, and the middle to late Pleistocene peak in base-level fall that could be related to changes in the Sulmona Basin and Pescara River systems.



## **Segmented oblique rift structure in the West Somali Basin, offshore Tanzania as new insight of a Neogene rift tectonic activity**

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*Keywords:* Rift, Basin, Oblique-rift, tectonostratigraphy, Offshore Tanzania, Mafia Basin.

Little is still known about the structural fabric of an offshore continuation of the East African Rift System (EARS) in the West Somali Basin, offshore Tanzania. During Upper Cretaceous, the seafloor/oceanic spreading of the Western Somali Basin ceased, and the Tanzania margin evolved into a passive margin until the Lower Oligocene when the EARS initiated. The offshore continuation of the EARS has been established mostly through sparse GPS measurements, earthquake slip vector data, the spatial distribution of earthquake focal mechanisms, and seismic reflection data. In detail, regional seismic reflection data highlight the presence of the continental-ocean crust transition west of Davie Ridge and across its northward prolongation, which is characterized by early Cretaceous reverse faults. In this contribution, we investigate a 3D seismic dataset located southern of Mafia Island and calibrated using few explorations well. The surface maps and structural mapping suggest a major structural style change during the Neogene. They are still active nowadays. Two recent and main interacting fault trends were distinguished: NS boundary fault corridors and an NW-SE internal arcuate segmented fault, both characterized by a widely and diffused distribution of normal fault with an overall cumulative amount of horizontal extension ranging between 5 to 10 km. Some of these faults appear to reactivate older extensional structures. However, the general absence of growth faults cutting across the Paleo-Neogene depositional units suggests a very recent rift re-activation. The recent rift system appears to show a component of obliquity concerning the orientation of the Davie Ridge, and the onshore structure related to the EARS tectonics.

## **Spatial-temporal migration of the central-southern Apennine belt and foreland basin system (Italy) constrained by Sr-isotope stratigraphy**

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*Keywords:* forebulge, foredeep, Strontium Isotope Stratigraphy, Apennines, fold-thrust-belt.

The Apennines form an active fold and thrust belt that develops as part of the W-Mediterranean subduction zone. The evolution of the collisional system is driven by the retreating subduction of the Alpine Tethys, which has caused the migration of compressive fronts and the opening of the Liguro-Provençal and Tyrrhenian back-arc basins, along with the rotation and translation of the Sardinia-Corsica and Calabria blocks. The Apennines form the northern limb of the Apennines-Calabria-Sicily orocline, developed due to the differential SE-ward retreat of the subduction system. In such a context, the central-southern Apennine system develops a foreland basin floored by a subaerial forebulge unconformity developed due to forebulge uplift and erosion. This unconformity is overlain by a diachronous sequence of three lithostratigraphic units made of: (i) shallow-water carbonates, (ii) hemipelagic marls and shales, and (iii) siliciclastic turbidites. Typically, the latter have been interpreted regionally as the onset of syn-orogenic deposition in the foredeep depozone, while little attention has been given to the underlying units. Accordingly, the rate of migration of the central-southern Apennine foreland basin-belt system has been constrained, so far, exclusively considering the age of the turbidites, which largely postdate the onset of sedimentation in the foredeep depozone.

In this work, we provide a new regional dataset of high-resolution ages obtained by strontium isotope stratigraphy applied to calcitic bivalve shells sampled at the base of the first syn-orogenic deposits overlying the forebulge unconformity. In this regard, we have investigated a transect of the Apennine belt, extending from inner to outer sectors, i.e. from Northern Calabria to South Majella massif, in order to constrain the timing and style of migration of the orogenic belt and foreland basin system. This dataset indicates progressive rejuvenation of the strata sealing the forebulge unconformity toward the outer portions of the belt. Also, integration with previously published data on syn-orogenic sediments of the area demonstrates that, among the different lithostratigraphic units of the foreland basin megasequence, dating the base of the post-forebulge carbonates is the best tool to constrain the style and rate of the foreland flexuring.

## Unveiling the structural architecture of the wedge-top Epiligurian Units in the Northern Apennines

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*Keywords:* Northern Apennines, Epiligurian Units, wedge-top basins.

The Northern Apennines are a seismically active accretionary wedge formed in response to the Late Cretaceous-Eocene closure of the Ligurian-Piedmont Ocean and the Oligocene-Miocene collision between Adria and Europe. The wedge is shaped by WNW-ESE-striking, SW-dipping thrusts accommodating bulk top-to-the NE tectonic transport. Since the Late Miocene, thrusting in the belt external domains acted coevally with extension in the western hinterland domain, where crustal thinning is still being accommodated by NW-SE-striking normal faults. The focal mechanism solutions of earthquakes between 8 and 35 km constrain NE-SW shortening in the frontal part of the wedge, whereas extensional tectonics controls the seismicity along the belt's axial portion and in the hinterland. Atop the deformed accretionary wedge occur the Epiligurian Units, which consist of middle Eocene-upper Miocene bathyal to shallow-water siliciclastic deposits infilling wedge-top basins. A regional unconformity separates pre- and post-Burdigalian sequences within the Epiligurian succession, with sedimentary facies changing from deep marine-to platform environment. Our mesoscale structural analysis shows compressional, extensional, and strike-slip fault arrays affecting extensively all the Epiligurian Units, with distinct structural features. Top-to-the NE, WNW-ESE-striking reverse faults are defined by commonly slickensided planar surfaces decorated by thin damage zones. Top-to-the SE, WSW-ENE-striking reverse faults are, instead, generally devoid of well-developed damage zones. NW-SE and NE-SW-striking normal and oblique faults systematically cut across the reverse faults and accommodate centimetric to metric throws. Common cataclastic and disaggregation deformation bands are associated with NE-SW striking normal faults cutting through Upper Eocene-Lower Oligocene siliciclastic units. On the other hand, calcite veins and fibres locally decorate NW-SE and NE-SW-striking normal and oblique faults in marly post-Burdigalian sequences, attesting to fluid-rock interaction within dilatant rock volumes during faulting. A remote sensing analysis has been performed on tectonic structures mapped at the regional scale and confirms a variable trend distribution and density for both normal and reverse faults within both the pre- and post-Burdigalian sequences. Our results suggest that these wedge-top basins probably evolved independently, influenced by lateral thickness variations of the stratigraphic sequences, erosion, subsidence rates and tectonics in response to regional and local variations of the stress regime within the underlying orogenic prism. We propose that the present-day framework of the Epiligurian Units can be used as a powerful structural-stratigraphic gauge to track down the variation, through time and space, of the tectonic regime and state of stress of the Apennines wedge, with noteworthy implications on its current seismotectonic setting.

## Synthetic seismic forward modeling as a tool to assess the seismic signature of carbonate-bearing fault zones

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*Keywords:* forward modeling, synthetic seismic, petrophysics.

Seismic images are fundamental to interpret subsurface setting on both continental and marine environments. However, in carbonate systems, seismic response can be very difficult to be analyzed due to the petrophysical heterogeneities, being the interpretation particularly complicated when faults are present. In fact, faults rocks are generally characterized by different petrophysical properties with respect to the host rocks. Synthetic seismic forward modeling is a powerful tool to quantifying the seismic response associated with fault-related petrophysical changes, since input parameters can be modified.

In this study, field and laboratory measurements are used to analyze the spectrum of the carbonate-bearing fault seismic response. Here, we focused on the carbonate ramp setting outcropping in the Majella Massif since it represents an excellent surface analogue of buried porous and faulted carbonate reservoirs worldwide.

Density and porosity were measured through a helium pycnometer on representative fault (damage zone) rocks sampled at increasing distances from fault planes. Investigated damage zone samples, show both increased and decreased porosity with respect to the host rock, depending on the single fault characteristics.

A 2D (12 km long) synthetic profile from the platform top to the basin, oriented SSE-NNW, was then carried out in Matlab simulating the outcropping architecture and spatial distribution of the sedimentary facies and of the faults. Together with a proper porosity variation related to facies distribution, the porosity along the damage zones (DZ) of the simulated faults was set according to the laboratory measurements. The low-frequency (40Hz) synthetic seismic profile shows marked diffraction hyperbolas in the modeled fault zones for faults characterized by higher porosity DZ where lower seismic velocity is expected. On the contrary, fault zone characterized by lower porosity DZ with respect to the host rock resulted to give a less clear seismic image. Going into the details, faults with decreased porosity and consequent increased seismic velocity of 1000 m/s in the damage zone respect to the host rock, do not show a visible difference in the seismic response if compared with the seismic image without modified petrophysical characteristics within the faults. On the other hand, faults with increased porosity and decreased seismic velocity of just 500 m/s respect to the host rock, show clear diffraction hyperbolas where their apexes correspond to the fault planes. Ongoing laboratory measurements and simulations changing geometries, thicknesses and orientations of the damage zones, are expected to help in improving the knowledge of fault seismic response. This work helps in bridging the gap between forward modeling and actual seismic imaging with large implications for hydrocarbon-reservoir characterization and the identification of potential CO<sub>2</sub> or hydrogen storage sites.

## The Pedalpine Backthrust in the western sector of the Southern Alps

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*Keywords:* Pedalpine Backthrust, Southern Alps, Po Plain, Nealpine phase.

During the construction of the “Monte Olimpino 2” railway tunnel between Grandate and Ponte Chiasso (Italy), the presence of a North verging reverse fault called Pedalpine Backthrust (Bernoulli et al., 1989) was detected. In the following years, the fault was mapped from the city of Como (Italy) to the city of Varese (Italy) (Bernoulli et al., 2018). The purpose of this study is to verify the extension of the backthrust along the southern margin of the western sector of the Southern Alps and to analyze its relationships with the structures of the neighboring Po Plain. The assessment of the Pedalpine Backthrust was performed through the interpretation of 2D seismic reflection profiles calibrated by wells data. The seismic interpretation highlighted the westward extension of the Pedalpine Backthrust, outlining a complex structural setting of “en echelon” reverse faults for a total length of more than 70 Km in the Lake Maggiore area. Furthermore, the study highlighted that the Pedalpine Backthrust is part of a deep triangle zone involving the Mesozoic carbonate units at the Southalpine margin. In addition, the backthrust is strictly associated, along a detachment plane at the base of the Cenozoic terrigenous units, to the Romentino south verging thrust in the central Po Plain area (Fantoni & Franciosi, 2010). The compressional architecture of this sector of the Southern margin of the Alps seems therefore to be different from the central sector of the Po Plain (Fantoni et al., 2004), probably due to the effects of different Mesozoic extensional structures. The genetic connection between the Pedalpine Backthrust to the Romentino south verging thrust allows the dating of the structural system. The two thrusts seem to have settled on the inner and outer edges of the nealpine foredeep with the main phases of growth referred to the Upper Oligocene and the Middle-Upper Miocene. In conclusion, it is possible to assert that the deactivation of the system is substantially pre-Pliocene in age.

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## **Paleostress analysis and history of the Voltri Unit in the Ligurian Alps (NW Italy) by comparing different stress inversion methods**

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*Keywords:* Fault-slip data, Stress inversion, TR method (TRM), Andersonian tensors, Ligurian Alps, Northwest Italy.

Published heterogeneous fault-slip data inverted by Federico et al. (2014) with the best-fit stress inversion methods provided by FSA (Célérier, 1999) and Win-Tensor (Delvaux, 2011) software are re-examined and analyzed with the TR method (TRM) (Tranos, 2015) for defining crucial differences in unraveling the paleostress history of a polyphase deformed region of the Voltri Unit of the Ligurian Alps. The TRM application using additional compatibility criteria on fault activations calculates site and bulk Andersonian stress tensors, which are compatible with each other and with the previously documented deformation in the area, in the absence of any tectonostratigraphic and overprinting criteria. In contrast, best-fit stress inversion methods based solely on the misfit angle (MA) minimization criterion, even with additional sophisticated techniques, like the Monte Carlo search method and R-optimization, calculate best-fit stress tensors that might have their principal stress axes deviating from the vertical direction (i.e., non-Andersonian) and might show substantial diversity among the different stations. These variations seem to be not due to real changes in the stress state but 'apparent' fault-slip data combinations, which are 'incompatible' with one another in terms of fault activation, especially in cases few fault-slip data are recorded at stations of limited spatial scale. More importantly, our analysis determines five distinct paleostress tensors that provide different paleostress history for the Voltri Unit and the Ligurian Alps. In particular, we define a transpression stress regime with NW-SE contraction in Late Eocene and an Oligocene E-W extensional regime, which fits with the E-W extension mentioned for the wider area north of Corsica, i.e., between Pyrenean and western Alpine domains, due to a major change in subduction dynamics (Lacombe & Jolivet, 2005). An N-S transtension, under which mutual permutations between  $\sigma_1$  and  $\sigma_2$  axes occur, gives rise to E-W contraction through strike-slip faults. This regime was considered a local or transition stress regime between the Oligocene E-W extension and the Miocene transpression. The latter defines the stress reorganization in the Ligurian Alps due to the decrease in the retreating rate of the Apennines slab, and it changed progressively from ENE-WNW to NNE-SSW contraction.

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## **S2.**

# **Evolution of sedimentary basins: an integrated approach**

*CONVENERS AND CHAIRPERSONS*

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*Gianluca Frijia (University of Ferrara)*

*Marcello Tropeano (University of Bari)*

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## The Numidian sandstones of the Molise area (Southern Apennines) in a source-to-sink perspective

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**Keywords:** Southern Apennines Chain, Numidian Sandstones, calcareous nannofossils biostratigraphy, detrital zircon U-Pb geochronology, sandstone petrology.

The Numidian Sandstones are a peculiar deposit made of ultra-mature quartzarenites, widespread throughout the western Mediterranean, from southern Spain and North Africa to southern Italy. In the southern Apennines, the Numidian Sandstones were deposited in the Lagonegro–Molise Basin.

Previous studies on the Numidian Sandstones in the southern Apennines have provided contrasting depositional ages encompassing the late Burdigalian and the Langhian and have debated different source areas. Most studies suggest that the onset of deposition is Langhian and a direct provenance from exclusively ancient African orogenies has been recently inferred based on detrital zircon ages and compositional features.

In this work, we report new biostratigraphic, geochronologic and compositional data from the northernmost deposits of the Numidian Sandstones in the southern Apennines. The analyzed stratigraphic section is located south of the Guardiabruna village (Molise Region). The study section belongs to the Tufillo-Serra Palazzo Unit. Here, the Numidian Sandstones are interbedded within medium to fine-grained bioclastic calcarenites and calcareous marls bearing planktonic foraminifera (Tufillo Fm.), which, in turn, conformably overlie the Varicoloured Clays.

Quantitative biostratigraphic analysis was performed on the calcareous nannofossils assemblages in twenty samples from the Numidian succession. The results allow us to refer the Numidian Sandstones deposited in the Tufillo-Serra Palazzo Unit to the upper Burdigalian-Langhian.

Preliminary detrital zircon U-Pb geochronological data of the Numidian quartzarenites reveal age spectra dominated by early Palaeozoic and older zircon populations similar to the Numidian sandstones exposed in northern Africa, but a few younger zircons, possibly Alpine and Hercynian in age, are also present. This suggests a mixture of sources from the African Craton and the western peri-Mediterranean Alpine chain. A mixed provenance is supported also by our heavy mineral and the petrographic data.

Concluding, the deposition of the Numidian Sandstones in the Molise area occurred in an open-marine foreland basin, interfering with the sedimentation of the Tufillo Fm. Their age is younger than the Numidian Sandstones from the Maghrebian Chain (lower Burdigalian). According to these data, we consider the quartzarenites sedimented within the Tufillo Fm. as recycled from the Numidian Sandstones of the Maghrebian Chain, as a consequence of the growing and unroofing North African Maghrebian belt.

## **High resolution rift sequence stratigraphy of Badenian sediments near Krčedin (Northern Serbia, Central Paratethys)**

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*Keywords:* Rift basin, high resolution sequence stratigraphy, Badenian, Middle Miocene, Central Paratethys.

Badenian (lower part of Middle Miocene) sediments are of paramount importance of defining the Central Paratethys in Serbia. The marine deposition in the Neogene of Serbia is limited to the Badenian age. The locality is situated on the easternmost slopes of Fruška Gora Mt., occupying the Koševac ridge. Badenian sediments are confirmed to date in this area at an outcrop along the road leading from Krčedin village to the Krčedin quarry. Coordinates of the outcrop are 45°10'5"N 20°8'15"E. The whole outcrop is not higher than 2m and contains four lithofacies, which is an excellent object for high resolution sequence stratigraphy. These sediments are part of a syn-rift climax system tract, according to the sequence stratigraphic scheme devised by Prosser (1993) and improved by Holz et al. (2017) to fit the rift tectonostratigraphic model. The basin basement is represented by Lower Cretaceous turbidites exposed at the Krčedin quarry, and the rift strata are overlain by Quaternary sediments (Anđelković, 2020).

Prosser (1993) defined the syn-rift sediments as belonging to the rift initiation or rift climax system tracts. So can we describe the found Badenian sediments. The lowest part of the series is represented by coarse-grained conglomerates belonging to the lithofacies A. It can be defined as rift initiation system tract because it represents the transgressive surface, probably bounded by the syn-rift unconformity (sensu Holz et al., 2017) at its base. Lithofacies B is represented by microconglomerates, which indicates less water energy and slightly more depth, so it would be convenient to assign it to the early rift climax system tract. Finally, lithofacies C (sandy marl) and lithofacies D (pure marl) can be found. They contain numerous planktonic foraminifera (*Orbulina suturalis*, *Praeorbulina* sp., *Globigerina* sp.), a much lesser amount of benthic foraminifera (*Borelis melo*, *Elphidium* sp.) and some ostracoda and gastropod fragments (Anđelković & Batočanin, 2020). These marls are remnants of a rapidly deepening basin and they can be described as middle rift climax system tract. After the Badenian age, the basin was rapidly inverted.

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## Diverse detrital quartz supplies in SE Alps: an FTIR study

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Keywords: FTIR Spectroscopy, detrital quartz provenance.

In this study 80 detrital quartz grains coming from 4 sedimentary rocks samples of the Julian Basin (JB) have been analysed. Quartz can incorporate chemical impurities as defects in the crystal lattice, with substitution of Si<sup>4+</sup> with H<sup>+</sup> and Al<sup>3+</sup> or B<sup>3+</sup>, by 4H<sup>+</sup>, and with LiOH. These substitutions form specific infrared absorption bands that can be investigated and analysed (Stalder & Konzett, 2012). Fourier Transform Infrared spectroscopy of quartz was used to investigate the sample set with interest to its OH defect speciation and content. OH defects are correlated to petrogenetic conditions, and they may be used as a provenance tool (Stalder, 2014). Polarized IR spectra can identify these different substitutions and allow to separate them from molecular water contained in fluid inclusions. Defect water contents were calculated for every different substitution (if present) by integration of the absorption area in the peaks' regions.

Julian Basin is a syn-orogenic basin in South-eastern Alps across Italian-Slovenian border, developed in the Late Cretaceous-Early Eocene. Quartz from the oldest sample (JB1; Maastrichtian) show a pattern suggesting a mixed source between igneous and non-igneous rocks, with a slight predominance of metamorphic material supply. Grains from sample JB17 (Thanetian) show the greatest variability in both defects and water content amount that suggests a different and more complex source. Quartz crystals from samples JB23 and JB26 (Ypresian) show a pattern of water-poor grains suggesting a mainly metamorphic rock type source. The peculiarity of JB17 is confirmed by several different previous studies based on both heavy minerals and geochemistry which demonstrated a strong difference in the supplies in the corresponding time interval (Lenaz et al., 2000; Lenaz & Princivalle, 2002; De Min et al., 2014; Velicogna, 2020).

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## **Burial history and diagenesis: stable-isotope and fluid inclusion constraints on the timing of diagenetic events in the dolomitized Dolomia Principale Norian, Southern Alps of Italy)**

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*Keywords:* subsidence curve, diagenesis, fluid inclusions, stable isotope, dolomitization.

Basin evolution results from geodynamic and depositional events, but also from the burial history, that may be reflected in the diagenetic history recorded in the sedimentary rocks: the multidisciplinary study of diagenetic phases coupled with basin analyses may provide constraints on the timing of these events.

The petrographic, cathodoluminescence (CL), stable isotope, and microthermometry investigation of inner platform facies of the pervasively dolomitized carbonate platform of the Norian (Upper Triassic) Dolomia Principale (Southern Alps, N Italy) identified two major dolomite phases. An early replacement fabric-retentive dolomite (D1 and D2, respectively replacing the sedimentary facies - from fenestral mudstone/wackestone to bioclastic packstone and mudstone and stromatolites- and early marine cements) is followed by a later, vug- and fracture-filling dolomite cement phase (D3, planar-s texture).

The fabric-retentive dolomitized carbonates (< 4 μm–30 μm, D1) and marine fibrous cements (30 μm–250 μm, D2) exhibit dull luminescence under CL whereas the burial dolomite cement (200 μm–500 μm, D3) exhibits zoned luminescence.

The δ<sup>13</sup>C values of the investigated dolomites (D1, D2, and D3) show a narrow range of variation (2.0 to 3.1 ‰ VPDB), pointing toward a fluid-buffered system. Differently, the δ<sup>18</sup>O values largely varies, ranging from –12.8 to +1.9 ‰ VPDB. In this range, D3 values cluster distinctively between –6.0 to –12.8 ‰ VPDB with respect to D1 and D2, which cluster from about –4 to +1.9 ‰ VPDB. The estimated oxygen isotope composition of the parent fluid of D1 and D2 (~0 to –5 ‰ VSMOW) suggests possible contributions from marine to slightly evaporated seawater, which is consistent with the arid climate and some basin restrictions suggested by earlier studies, whereas that of D3 (+1 to +5 ‰ VSMOW) is consistent with burial fluids.

Microthermometric measurements of the primary two-phase fluid inclusions in D3 yielded a mean homogenization temperature of 112.4 ± 8.2°C.

These results can be framed in the burial history of the studied basin, providing constraints on the timing of the diagenetic events. Supposing a surface seawater temperature of at least 20-25°C and a geothermal gradient of about 40°C/km (during the Early Jurassic rifting that led to the opening of the Alpine Tethys) such temperature might be reached at reasonable burial depth ranging from 2.0 km to about 2.5 km. According to the subsidence curve this depth, compatible with the temperature recorded by the fluid inclusions, was reached during the Early Jurassic, with D3 cement precipitation causing a significant reduction of the porosity.

The followed integrated approach highlights the possibility to better characterize the occurrence of multiple diagenetic events in time and space, as well as their feedback effects on the porosity evolution of dolomitized carbonate reservoirs, framing the diagenetic events at basin scale.

## Relative sea-level variations and basin evolution during the Messinian Salinity Crisis (Crotona and Rossano Basins - North Calabria)

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*Keywords:* Messinian Salinity Crisis, sequence stratigraphy, basin modeling.

An integrated analysis of subsurface dataset and outcropping successions permitted to define a stratigraphic and paleogeographic evolutionary model of the wedge-top Rossano and Crotona Basins during the Messinian Salinity Crisis (MSC). The presence of complete sea-level controlled successions, indicate the dominance of the eustatic signal in the basin evolution, in comparison with the synsedimentary tectonic input, which played only a secondary role consisting in the strong basinward shift of facies caused by fast decreasing in the accommodation space.

In particular, during the late Tortonian - early Messinian the studied basins were characterized by open normal marine conditions, as suggested by the widespread deposition of deep-water claystones followed by diatomites (Tripoli Fm). The first basin restriction occurred during the early Messinian at ca. 5.96 Ma, as a consequence of the sea-level relative still stand, that triggered the deposition of a carbonate platform system (Calcare di Base Fm - CdB). The latter was characterized by sabkha to shallow-water environments, dominated by microbial carbonate and evaporite deposition, passing into a gentle slope to basin setting in which resedimented and pelagic deposits occurred.

A successive regional sea-level drop, dated at ca. 5.60 Ma, induced a general exposure of the CdB platform system and the creation of a marked erosional surface generally known as the Messinian Erosional Surface (MES). Consequently, during the early LST, a thick prograding wedge deposited and, due to the reduction of the connections with the open sea, new more severe restricted conditions of the basins took place.

Later, during the late LST, the massive deposition of salt dominated bodies reshaped the basin paleotopography and the depocentres were filled, thus sealing the previous irregularities of the paleo-seascape and creating roughly flat plains without deep depozones.

Afterwards, a renewed transgression phase (TST) inundated again the basins, causing firstly the sedimentation of clay dominated deposits, and later, during a further HST, the reestablishment of evaporitic conditions and the deposition of widespread shallow-water sulphate deposits.

Lastly, a new severe relative sea-level drop (LST) exposed again all the previous deposits, as testified by the superimposition of alluvial conglomerates along paleovalleys incised into the underlying HST sulphates. This event marks the transition to the so-called Lago-Mare event that typifies the last stage of the MSC, which definitely terminates with the reflooding of the Mediterranean at the Pliocene transition (ca. 5.33 Ma).



## **Decoding seafloor and paleoclimate conditions from the paleo-Adriatic domain during early Messinian (Majella, Apennines, Italy)**

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*Keywords:* facies analysis, carbonates, Miocene, Majella, paleoclimate.

The different environmental conditions produced by the progressive restriction at the Mediterranean-Atlantic gateways during the early Messinian are abundantly investigated in the deeper water succession, while the shallow-water record is less explored. Throughout the Mediterranean, the pre-evaporite deposits in the deep-water record display changing lithologies, from hemipelagic marls and limestone alternation to sapropelitic marly limestone and euxinic clays. The shallow water successions are generally characterised by luxurious coral reefs developed in the Mediterranean area, with some, locally restricted, exceptions. During the early Messinian a first record of the progressive decay of trophic conditions in shallow water environment has been reported in the Majella structure (Central Apennines, Italy). Here the lower Messinian is represented by the *Lithothamnion* Limestone carbonate ramp that constitutes the uppermost carbonate unit of the Bolognano Formation. This ramp developed in the paleo Adriatic sea and it was characterised by a wide middle ramp environment in which coralline algae dominated carbonate production. This facies was associated with seagrass meadows colonizing the inner ramp. The outer ramp was characterized by bioturbated hemipelagic marl with planktonic foraminifera, pectinids and brachiopods in the aphotic zone.

In this work we present facies and geochemical data providing evidence for an early, and repeated, onset of a restrictive environmental development, characterising and the *Lithothamnion* Limestone carbonate ramp. A stratigraphic section of ramp succession was measured in the eastern sector of Majella structure (Taranta Peligna), forty bulk-rock samples were analysed for carbon isotopes then correlated with Mediterranean stable isotope record. Redox-sensitive elements (ICP-MS) was performed on twenty-five bulk rock samples. On these samples the Total Organic Carbon (TOC) was also measured using the Loss-On-Ignition (LOI) techniques. The foraminiferal content was analysed under a binocular microscope and classified for bio/chronostratigraphic attribution.

The general negative carbon isotope trend recorded of the investigated section is interpreted as the record of the final stage of the Late Miocene Carbon Shift. Trends in the redox-sensitive elements are indicative of an evident decrease in bottom-water oxygen content and coinciding with the drowning of *Lithothamnion* Limestone carbonate ramp. The drowning coincides with the occurrence of *Globorotalia nicolae* (MMi 13b zone), when a conspicuous terrigenous input marked by a spike of Al and TOC content was recorded in the investigated succession.

## Trunk river and tributary interactions and implications for coarse vs fine-grained sediment storage in the Po alluvial basin (northern Italy)

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*Keywords:* Trunk river, tributaries, subsurface stratigraphy, core correlation, sediment provenance, Pleistocene-Holocene.

The mutual relations between the trunk river and its tributaries may influence grain size and composition of sediments stored in the subsurface of alluvial plains. Although tributary rivers can supply large volumes of clastic material to alluvial basins, the preservation potential of tributary-river deposits is highly debated. The Po Plain is fed by the Po River and by a dense network of transverse tributaries draining the nearby Alpine and Apennine chains. Stratigraphic, sedimentological, petrographic and geochemical analyses on core sediments permitted to: (i) characterize the three-dimensional geometry and composition of Po and Apennine sedimentary units; (ii) examine the patterns of sediment dispersal and depict the major shifts in sediment provenance between the Po–Alpine and Apennine river systems; (iii) estimate the extent to which tributary rivers contributed to sediment accumulation in the Po alluvial basin; (iv) discuss the main factors that influenced sediment deposition and preservation by the Po River and tributary systems since the Middle Pleistocene. Po River deposits are aggradationally stacked channel-belt sand bodies with high contents of quartz–feldspar and metamorphic rock fragments, combined with high chromium levels. These sand bodies, 20 to 30 km wide, are replaced southward by finer-grained deposits supplied by the distal Apennine tributary-rivers system. Apennine sands, confined in narrow ribbons, show lower quartz–feldspar contents, abundant sedimentary lithics and lower chromium levels. In the last 870 kyr, the boundary between the Po and the Apennine sediment delivery systems shifted along a north–south axis in response to distinct controlling factors. From ca 870 to 450 kyr BP, the Po River flowed close to the Apennine chain and Apennine-rivers deposition was restricted to a relatively narrow area of the plain. Soon after 450 kyr BP, the Po channel belt shifted northward by more than 20 km, probably in response to a prominent tectonic event. Since then, Apennine rivers deposited large volumes of fine-grained material over a considerably larger area than before. This area periodically narrowed and enlarged in response to glacial–interglacial oscillations. In particular, Po channel-belt widening during glacial periods reduced the area for Apennine rivers sedimentation. A 25–30 km wide channel-belt sand body was deposited by the Po River between ca 52 and 14 kyr BP. The Po channel-belt progressively narrowed after the glacial culmination. During the Holocene, Po channel patterns became avulsive and distributive. Narrow channel belts (<3 km) formed along the Po River branches and abundant swamp and poorly drained-floodplain muds accumulated in interfluvial areas. The temporary deactivation of the southernmost Po river branches resulted in the sharp widening of the area available for Apennine river sedimentation and permitted the intrusion of Apennine sediments in the former Po River domain.

## **Megaflod deposits in sedimentary basins evolution. The case of the Messinian-Zanclean seismic stratigraphic unit in the Ionian basin**

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*Keywords:* Messinian, Zanclean, Ionian Basin, Mediterranean, megaflod deposits.

In the western Ionian Basin, a wedge-shaped seismically transparent to chaotic unit has been mapped at the foot of the Malta Escarpment extending and thinning towards the east on the outer reaches of the Calabrian accretionary wedge. Its thickness, assuming realistic values of seismic velocity, exceed 800 m in the depocenter, and the volume is ~ 1600 km<sup>3</sup>. Its stratigraphic position has been assigned variably between the upper Messinian (deformed evaporites, mainly gypsum; Butler et al., 2015) and lower Pliocene (olistostrome; Polonia et al., 2011). A number of recent publications (Micallef et al., 2018, 2019; Garcia Castellanos et al., 2020; Spatola et al., 2020; Camerlenghi et al., 2020; Rebesco et al., in review) have proposed the hypothesis that this unit is the sedimentary expression of the Zanclean megaflod of the Mediterranean that ended the Messinian Salinity Crisis (e.g. Garcia-Castellanos et al., 2007). A number of observational, theoretical (numerical modelling) and conceptual arguments support his hypothesis, contributing to the discussion on the role of megaflods in the evolution of Earth terrestrial and marine sedimentary basins, and for comparison, on planets. We review the arguments in favor of the megaflod hypothesis and illustrate how we plan to verify it through scientific ocean drilling, proposing that a cross-disciplinary effort should be made to shed light on what could be the largest megaflod deposit so far identified on Earth and on the role of rapid sealevel changes in marine sedimentary basin evolution.

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## The Pescara incised valley system: Insights from an onshore sector of the S2S Po-Adriatic sediment routing

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*Keywords:* Source-to-sink systems, Incised valley fill, Coastal plain, facies analyses.

Incised valley-fill (IVF) systems play a key role in source-to-sink (S2S) sediment transport towards sedimentary basins (Blum et al., 2013).

A buried paleovalley system, about 3.5 km wide and 50 m deep, was reconstructed below the Pescara River coastal plain (central Adriatic). The study area represents an onshore sector of the larger-scale S2S Po-Adriatic system and is located in front of the Mid-Adriatic Depression basin. The paleovalley profile, incised into the marine Upper Pliocene-Lower Pleistocene bedrock, and the 3D IVF facies architecture were reconstructed through a multi-proxy approach based on stratigraphic, sedimentological and palaeontological data. To refine stratigraphic and paleoenvironmental reconstructions, a new continuous core was recovered from the paleovalley depocenter and samples were collected for radiocarbon dating and facies analysis.

At different depths below the surface, paleovalley flanks are characterized by fluvial terraces made of gravel bodies with upper flat surfaces. These terraces, most likely incised by the Pescara river during the stepwise sea-level fall that followed the last Interglacial (MIS 5e, about 125 ky BP), are interpreted as falling stage systems tract (FSST) deposits. The valley floor is composed of a laterally extensive gravel body, > 10 m thick, that accumulated during the Last Glacial Maximum (28-20 ky BP, MIS 2). This fluvial deposit represents the lowstand systems tract (LST). Above LST deposits, the transgressive systems tract (TST) shows a deepening-upward trend, from poorly-drained (alluvial) to estuarine facies associations (early to late TST). The estuarine succession is characterized by very soft (< 1 kg/cm<sup>2</sup>) and organic-rich silty clays, linked to the post-glacial sea-level rise, when the Pescara paleovalley was progressively drowned and an estuary formed in the study area. The uppermost part of the IVF and Pescara coastal plain Holocene succession is composed of coarse-grained (sands and gravels) fluvio-deltaic deposits. The base of this stratigraphic interval coincides with the beginning of deltaic progradation at the onset of the Holocene (MIS 1), and can be interpreted as the Maximum flooding surface (MFS). Thus, prograding fluvio-deltaic sediments are the highstand systems tract (HST).

Glacio-eustatic fluctuations (over the last 125 ky) are considered the main driving factor that induced river down cutting during sea-level fall and subsequent valley filling during sea-level rise.

This study represents the starting point of a more complex basin-scale study, where onshore data will be correlated to their offshore equivalents to better understand sediment dynamics within the Po-Adriatic S2S system.

Blum M., Martin J., Milliken K. & Garvin M. (2013) - Paleovalley systems: insights from Quaternary analogs and experiments. *Earth-Science Reviews*, 116, 128-169.

## **Tectonic-Sedimentary evolution of the Tuscan shelf: seismic-stratigraphic analysis of Neogenic succession in the norther Tyrrhenian sea (Elba Island - Argentario)**

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*Keywords:* northern Tyrrhenian Sea, Tuscan shelf, Neogenic basins, seismostratigraphic units, unconformities, evolutionary model, extensional tectonics.

A 2D and 3D re-interpretation of vintage seismic profiles acquired during the 1970s in the area of the Northern Tyrrhenian Sea between the Elba Island and the Argentario promontory was performed to build a 3D models of the main structures characterizing the Tuscan shelf. Stratigraphic information were extracted by the Pianosa island surface geology along with the Martina-1 and Mimosa-1 exploration wells. We identified eight seismostratigraphic units separated by eight unconformities. Among these seismostratigraphic units, two represent the pre-Neogenic foundation while six post-orogenic units represent the Neogenic succession covering the Tuscan shelf. The main shallow structures of the area are the narrow, mostly N-S and NE-SW trending Neogenic basins of Montecristo, Punta Ala and Uccellina, where the post-orogenic seismostratigraphic units deposited. Effort has been done to unravel the relationship between the position and evolution of the basins with previous compressive structures, mostly consisting in deep East-verging thrusts belonging to a previous compressional phase. Intriguingly, and partially in contrast with the literature works in the area, no evidence of listric and low angle fault systems were observed. A new evolutionary model of the Tuscany shelf was then proposed. In this view the formation of the Neogenic basins began in the upper Burdigalian initially as intermontane basins developed along the flanks of the antiforms formed during the compressive tectonics. The position of the basins, usually recovered at the forelimb vs. the backlimb of the thrust antiforms, influenced the asymmetrical or symmetrical shape during their evolution. Starting from the Messinian, we observe a general collapse of the platform, which leads to the deepening of the basins driven by the normal high-angle bordering faults. This process continues up to the lower Pliocene, when the deactivation of all normal faults is recorded, and conditions of widespread subsidence are clear throughout the platform, together with the deposition of the two more post-orogenic units. In this contribution we reviewed the tectonic evolution of the northern Tyrrhenian Sea posing new questions both on the mechanisms responsible for the extensional processes and on the structures which impacted on such arrangement, also establishing a new starting point for a full unravelling of the Tuscan Shelf evolution. A 2D and 3D re-interpretation of vintage seismic profiles acquired during the 1970s in the area of the Northern Tyrrhenian Sea between the Elba Island and the Argentario promontory was performed to build a 3D models of the main structures characterizing the Tuscan shelf. Stratigraphic information were extracted by the Pianosa island surface geology along with the Martina-1 and Mimosa-1 exploration wells. We identified eight seismostratigraphic units separated by eight unconformities. Among these seismostratigraphic units, two represent the pre-Neogenic foundation while six post-orogenic units represent the Neogenic succession covering the Tuscan shelf. The main shallow structures of the area are the narrow, mostly N-S and NE-SW trending Neogenic basins of Montecristo, Punta Ala and Uccellina, where the post-orogenic seismostratigraphic units deposited. Effort has been done to unravel the relationship between the position and evolution of the basins with previous compressive structures, mostly consisting in deep East-verging thrusts belonging to a previous compressional phase. Intriguingly, and partially in contrast with the literature works in the area, no evidence of listric and low angle fault systems were observed. A new evolutionary model of the Tuscany shelf was then proposed. In this view the formation of the Neogenic basins began in the upper Burdigalian initially as intermontane basins developed along the flanks of the antiforms formed during the compressive tectonics. The position of the basins, usually recovered at the forelimb vs. the backlimb of the thrust antiforms, influenced the asymmetrical or symmetrical shape during their evolution. Starting from the Messinian, we observe a general collapse of the platform, which leads to the deepening of the basins driven by the normal high-angle bordering faults. This process continues up to the lower Pliocene, when the deactivation of all normal faults is recorded, and conditions of widespread subsidence are clear throughout the platform, together with the deposition of the two more post-orogenic units. In this contribution we reviewed the tectonic evolution of the northern Tyrrhenian Sea posing new questions both on the mechanisms responsible for the extensional processes and on the structures which impacted on such arrangement, also establishing a new starting point for a full unravelling of the Tuscan Shelf evolution.

## Fault-controlled deposits: an overview

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*Keywords:* fault-controlled deposits, coarse-grained systems, facies analysis, vertical and lateral variability.

Fault-controlled deposits are important in basin analysis because they are prone to record tectonic events and changes in sea-level that operated during basin evolution. They also represent reservoir targets for CO<sub>2</sub> storage and exploration of energy resources.

Fault-controlled systems develop in tectonically active basins forming tens to hundreds of meters thick coarse-grained wedge-shaped successions. Usually, the higher the syn-depositional cumulative displacement created by the fault, the thicker the deposit stacks. Fault-controlled deposits are typically physically disconnected from their more proximal counterpart located on the footwall, although genetically linked to it.

Fault-controlled Gilbert- and shelf-type deltas and base-of-slope deposits have been recognised and documented in both modern and ancient systems but little emphasis has been dedicated to the embryonic phase reflective of an unsteady state. Neither is a model available for the prediction of the evolution of these depositional systems through time and space. Using a triangular diagram having discrete categories representing end-members (i.e. Gilbert- and shelf-type delta and base-of-scarp systems) infinite numbers of mixed systems can be produced depending on the interaction among sedimentary supply, relative sea-level changes, and extensional rate (Chiarella et al., 2021).

Using subsurface and outcrop examples, the vertical and lateral evolution along the controlling fault, as well as the internal architecture and typical facies tract related to the different depositional stages and the final end-member of the fault-controlled systems are presented. Analysis at seismic, outcrop and facies scale show that understanding the interaction between fault-activity and sedimentation is fundamental for the correct reconstruction of the basin evolution and prediction of reservoir scale properties (e.g., Thomson et al., 2020) of fault-controlled systems.

The project is part of the ‘Fault-controlled deposits’ Joint-Industry project supported by Aker-BP, DNO, Neptune Energy, and Spirit Energy.

Chiarella D., Capella W., Longhitano S.G. & Muto F. (2021) - Fault-controlled base-of-scarp deposits. *Basin Research*, 32, 1056-1075, <https://doi.org/10.1111/bre.12505>.

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## **Role of Early Jurassic rift architecture in the dispersal of calciturbidites, as revealed by geological mapping in Central and Northern Apennines**

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*Keywords:* Jurassic; Apennines, rift basins, calciturbidites, dispersal patterns, pelagic carbonate platform, geological mapping.

The role of sea-bottom topography in the dispersal of shallow water-derived calciturbidites across a submarine rift, as determined by the local extensional architecture, is under-investigated, namely with pelagic settings along ancient passive continental margins. A comparison with modern carbonate platform/basin analogues, or with siliciclastic systems, is not always feasible, as ancient carbonate systems were commonly home to anachronistic environments (e.g. the Western Tethyan Mesozoic). Geological mapping of the Jurassic rift basin exposed in the Apennines of Central Italy revealed a complex pattern of intrabasinal highs (pelagic carbonate platforms) and intervening basins, controlled by the high density, and oddly variable trends, of faults rooted in a shallow detachment layer corresponding to thick Triassic salt. A map pairing the occurrences of resedimented beds in pelagic successions with an updated palaeogeography becomes therefore the natural descriptor of the itineraries followed by sediment gravity flows. This qualitative method represents a companion, or even alternative, approach to the one strictly based on physical stratigraphy, and it greatly improves our knowledge of regional geology and rift-basin analysis. Our study focuses on: i) a reconstruction of the palaeotectonic architecture of the Umbria-Marche Basin in the Jurassic, and on ii) how this architecture produced a submarine topography which governed the dispersal of sediment, shed by the neighbouring Lazio-Abruzzo Carbonate Platform, for >40 million years. Geological mapping, coupled with the measurement and correlation of stratigraphic sections, shows that the marginal palaeoescarpments of pelagic carbonate platforms formed obstacles to the gravity flows as sediment load was discharged in confined basins at their toes and/or flows were deflected and forced along alternative itineraries. While turbidity currents were locally vigorous enough to climb the escarpments, leaving graded and laminated overbank deposits on the pelagic carbonate platform-tops, a "shelter" effect is evidenced by the resediment-free nature of those basins lying downflow, which were shielded by the highs. Our case study potentially represents the analogue of hydrocarbon fields both inland and in the offshore.



## **Diagenetic destruction of porosity in Quartzofeldspathic sandstones, Miocene Cilento group, Southern Apennines foreland basin system**

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*Keywords:* Cilento Group, southern Apennines, turbidite systems, sandstone composition, diagenesis, pore system, burial history.

The Cilento Group (Langhian-to-Tortonian) is a thick turbiditic succession (1200-2500 m) of the Southern Apennines foreland region that unconformably overlain the Lucanian oceanic terranes. It has been divided into four formations from NW to SE: the Pollica, San Mauro, Torrente Bruca and Albidona formations. Here, the post-depositional history of the upper portions of the Cilento Group, the San Mauro Formation (SMF), is discussed.

The SMF consists of 1400-1600 m thick succession characterized by three main turbidite facies associations: outer-fan, middle-fan, and inner-fan. The outer-fan facies association characterizes the lower part SMF and is made by 300-500 m of thin-bedded sandstones and thick mudstones and marlstones. Numerous intrabasinal carbonate turbidite beds paired with a coarse-grained volcanoclastic layer are interbedded with the outer-fan deposits. The middle-fan facies association define the middle part of the SMF and is represented by a section of about 700 m thick sandstone-lobe turbidite beds and thin fan-fringe deposits. Two impressive intrabasinal carbonate megaturbidite beds, 65 m and 35 m in thickness, respectively, are interbedded with sandstone-lobe strata. The inner-fan facies association typify the upper part of the SMF and is characterized by 400-500 m thick succession of channelized coarse-grained sandstone and conglomerate turbidite beds.

Sandstones are generally characterized by quartzolithic, volcanolithic and quartzofeldspathic composition, whereas hybrid arenites and calcarenites characterize the carbonate megabeds.

Several diagenetic processes reducing porosity and permeability, such as compaction and cementation, occurred within the SMF. In particular, framework grains result deeply compacted, as testified by the common deformation of ductile grains (mainly micas) and detrital matrix. Cementation occurred through the precipitation of different minerals. The main cements are: 1) carbonate, such as calcite and less dolomite, playing an important occluding role along intergranular space, even running a quite replacement in quartz and feldspar grains ; 2) authigenic quartz occurring as little overgrowths or as minor mosaic quartz; 3) phyllosilicates, mainly developing in the upper part of SMF as pore filling chlorite cement or as small and incomplete illite coatings on skeletal grains; 4) Fe-oxides occurring as pathchy or pore-filling cements.

The pore system consists of inter-intra-granular pores with a small pore radius and fractures. The relationship between the compactional porosity loss (COPL) and the cementational porosity loss (CEPL) testifies that compaction is the main reduction porosity process for SMF sandstones. Burial analysis suggests two phases of intense subsidence, interpreted as the result of syn-orogenic extension at shallow crustal levels intermitted by periods of low sedimentation rates, linked to gravitational instability of a vertically growing orogen.

## **PALEOSTRIPv1.0 - a user-friendly 3D backtracking software to reconstruct paleo-bathymetries**

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*Keywords:* Backstripping, reconstructing paleo-bathymetries, basin analysis, numerical modeling, open-source code.

We present PALEOSTRIPv1.0, a MATLAB open-source software designed to perform 1D, 2D and 3D backtracking of paleo-bathymetries. PALEOSTRIP comes with a Graphical User Interface (GUI) to facilitate computation of sensitivity tests and to allow the users to switch on and off all the different processes and thus separate the various aspects of backtracking. As such, all physical parameters can be modified from the GUI. It includes 3D flexural isostasy, 1D thermal subsidence and possibilities to correct for prescribed sea level and dynamical topography changes. In the following we detail the physics embedded within PALEOSTRIP and we show a few applications on a drilling site (1D), a transect (2D) and a map (3D), taking the Ross Sea (Antarctica) as a case study. PALEOSTRIP has been designed to be modular and to allow users to insert their own implementations.

## **The Upper Pennsylvanian to Middle Triassic continental succession in SW Sardinia: new key sections, stratigraphic-sedimentological refinements, and petro-sedimentary notes**

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*Keywords:* sedimentology, stratigraphy, continental environments, provenance studies, SW Sardinia.

Stratigraphical-sedimentological investigations of new and old outcrops allowed to better reconstruct the post-Variscan Upper Pennsylvanian to Middle Triassic succession in SW Sardinia. It starts with the Upper Pennsylvanian limnic San Giorgio Fm (Lower Rotliegend), formed by alternations of coarse- to medium-grained siliciclastics. Intercalations of carbonates and volcanic rocks are present. The unit deposited in a narrow warm-wet alluvial-to-lacustrine collapse basin. The Early – Middle (?) Permian red bed Guardia Pisano Fm (Upper Rotliegend) follows: pelites, sandstones, and rare conglomerates are represented. Volcanic rocks are rare. The unit was deposited in a warm-arid alluvial environment of mid-to low-energy. The Guardia Pisano Fm is followed by the red bed Upper Permian – Lower Triassic red bed Rio Is Corras Fm (Sardinian Buntsandstein Group?). It is formed by conglomerates and calcretes with rare sandstones, pelites, and evaporites. This unit deposited in a warm(hot?)-arid fan-delta to lake environment of variable energy. Stratigraphic type-sections have been described for all the mentioned units. Scattered red beds of the Guardia Pisano Fm or the Rio Is Corras Fm are often unconformably posed over the Variscan Cambrian carbonates reliefs. Examples are known in all the SW Sardinia. At Guardia Pisano the limnic fine deposits of the upper San Giorgio Fm are covered through a weak unconformity by the Guardia Pisano Fm red beds pointing to a smooth climatic and environmental transition. The new outcrops found in the S.Giorgio basin area (Iglesias) represent the missing link between the formerly described stratigraphic units. Here the Rio Is Corras Fm conglomerates are conformably posed over red bed alternations of pelites, sandstones, conglomerates, carbonates, and evaporites representing the upper prosecution of the Guardia Pisano Fm: they mark a gradual passage from a low-energy playa to a fan delta - lake environment. Preliminary petrographic analysis of the S. Giorgio sandstones classify them as litharenites and sublitharenites. Calcilithites have been found. The Guardia Pisano sandstones are litharenites and minor subarkoses. The Rio Is Corras Fm rare sandstones are all calcilithites. Compositional and textural maturity trends in times suggest repeated cycles of reworking of the landscape under a (warm-hot?) wet to dry climate. The almost undisturbed superposition of the various units on each other, the growing areal extent in times of the outcropping units area from the Rio S. Giorgio Fm to the Rio Is Corras Fm, the unconformable setting of the younger units also on the basement with the growing distance to the hypothesized main depocenter (S. Giorgio area?), suggest a progressive widening of this depositional continental basin in times, starting as a narrow basin in Late Pennsylvanian times and merging in the end with the wider extensional basins related to the W-Tethys rifting. Subsurface data by drills suggest at least 350 m of thickness.

## **Development of a unified geographic database from separated existing data through open-source softwares, Crotona Basin, Southern Italy**

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*Keywords:* GIS, subsidence, Crotona Basin, Calabria.

The Crotona Province (Calabria - South Italy) extends for a total surface of circa 1.736 km<sup>2</sup> in which a wide spectrum of geological, geomorphological and tectonic configurations alternate from the mountainous hinterland portions towards the coastal plain settings. Through the integrated collection of data coming from separated databases such as Geoportale della Calabria, Geoportale Nazionale, Videpi Project, ARPACAL Multirisk Functional Center, CARG project, CASMEZ, a complete geodatabase which make available a wealth of different spatial and cartographic data useful for the study and monitoring of Province of Crotona was implemented through open source technologies such as Qgis and PostgreSQL.

The processed data consist in:

- 1) A new unified Geological map obtained through the comparison of the CASMEZ 1: 25000 and CARG the 1: 50000 maps and the reinterpretation of the stratigraphies with the adaptation of the old nomenclature with the new standards defined by the CARG project;
- 2) Geomorphological map obtained through the integration of the available bibliography with new data coming from geoportale della Calabria;
- 3) Topographic and land cover maps obtained through the processing of both national and regional data;
- 4) Aspect, Slope and Curvature maps of the studied territory obtained using the Digital Elevation Models (DEM);
- 5) Rainfall and drainage density maps obtained through the re-elaboration of the ARPACAL databases;
- 6) Subsidence and land movements maps obtained through the processing of the ascending and descending orbit of RADARSAT 1 and 2 (Band C) satellites (2013-2018) using PSP-DIFSAR technique, and the ascending orbit of the TerraSarX satellite (X Band) and the descending orbit of the CosmoSkyMED satellite (X Band) (2013-2018) using SBAS technique. Lastly, using the qgis2web plugin an interactive WebMap was created with the final aim to disclose, query and interactively view as much information as possible from a single database which also allows periodic updating without major investments and with very low maintenance costs.

## **Investigations on the emplacement mechanisms of the Eocene olistoliths of the Miramare Castle (Trieste, Italy)**

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*Keywords:* flysch, olistoliths, debris flow, Friuli carbonate platform.

Eocene flysch deposits are widespread in north-eastern Italy, Slovenia and Croatia and represent the sedimentation in the foreland basin of the Dinaric chain. Flysch extensively outcrops in the surroundings of Trieste at the front of the Carso Anticline. The Carso Anticline is a large NW/SE trending structure in the thick carbonate succession of the Friuli Carbonate Platform, a shallow water carbonate domain representing the northeastern termination of the large Adriatic Carbonate Platform that stretched from northeastern Italy to Montenegro and hosted shallow water sedimentation for large part of the Mesozoic and the Cenozoic.

A rather unknown peculiarity of the Trieste flysch succession is that at Castle of Miramare, in the vicinity of Trieste, it is found in association with a series of large calcareous blocks that make up the promontory on which the castle is built. Approximately, a hundred calcareous blocks having volumes ranging from about 500,000 m<sup>3</sup> to 1,300,000 m<sup>3</sup>, were identified in previous mapping campaigns. Tonelli (2001) highlighted that the blocks are made of Eocene platform limestone belonging to the Miliolid, Alveolinids and Nummulites Limestone. The Miliolids, Alveolinids and Nummulites Limestone represents a phase of carbonate deposition that took place when the Friuli Platform in this sector was influenced by fore-bulging of the Dinaric chain that was advancing from the northeast. The blocks overlie and are overlain by flysch, thus testifying that their deposition was, at least in part, contemporaneous to that of the flysch itself. The presence of marly conglomerate lithofacies, in places associated to the blocks, has been interpreted as the matrix of a cohesive debris flow of which the calcareous blocks are olistoliths. Whereas the blocks have been mapped and some of their features identified, the mechanisms of their deposition are not yet completely understood. In this contribution, we present new data concerning the characteristics of the calcareous blocks, their spatial relationships with the flysch and the associated deformations that help shedding light on the processes that operated during the emplacement of the Miramare olistoliths.

Tonelli N. (2001) - L'origine dei blocchi calcarei del parco di Miramare (Trieste). Tesi di laurea inedita. Università degli Studi di Trieste.

## Using multi-proxy thermal maturity datasets to validate deformation styles from the Adjara-Trialeti fold-and-thrust belt to the Greater Caucasus (Georgia)

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*Keywords:* thermal maturity, intra-continental deformation, Maikop, Kura Basin, Caucasus.

We present a brand new multi-proxy dataset of thermal maturity indicators, which derive from the application of several analytical techniques on surface and subsurface sedimentary successions. The study area spans from the Greater Caucasus to the Adjara-Trialeti fold-and-thrust belt (FTB), comprising the intervening western Kura Basin, in Georgia, and represents a region of continental deformation in the hinterland of the Arabia-Eurasia collision zone. Original and published clay mineralogy, Raman spectroscopy and petrography on dispersed organic matter, and pyrolysis data are integrated for the first time in a coherent tectono-sedimentary scenario. Thermal maturity spans from the low diagenetic realm (60-80°C) in the Upper Miocene section of the Kura sedimentary fill, to the oil window in the Cretaceous to Lower Miocene successions of Adjara-Trialeti FTB, Kakheta ridge and Kura Basin (70-120°C), up to about 400°C in the Greater Caucasus core. Integration of different indicators, besides allowing the estimation of maximum burial temperatures acquired through time, enabled to draw the tectonic evolution of the area. Different maturity trends and thermal histories, coupled with structural and stratigraphic data, highlight that the study area comprises two domains derived from positive tectonic inversion: the E-W Adjara-Trialeti doubly-verging FTB from an Eocene back-arc rift basin and the SSW-verging Georgian Greater Caucasus from a Mesozoic rift basin. Between the two, thin-skinned south-verging thrusts deform the Kura Basin and the Kakheta ridge successions, originally deposited on an extensional structural high which was later flexured during compression. The similar thermal maturity degree in the Adjara-Trialeti FTB and the Kakheta ridge/Kura Basin areas has been acquired in different time spans: during Paleogene extension and during Miocene thin-skinned shortening, respectively. The results indicate that thermal maturation of the sedimentary successions in the Adjara-Trialeti FTB can be ascribed to burial during rift evolution. The same conclusion can be drawn for the axial zone of the Greater Caucasus, whereas tectonic overburden may have contributed to the thermal maturity of the rocks in the southern foothills of the Greater Caucasus: this area needs further work to assess its tectonic evolution.

## **Sedimentological and biostratigraphic characterization of the Paludi Formation (Longobucco Basin, north-eastern Calabria): proto-Apenninic shortening of an Alpine foredeep?**

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*Keywords:* Longobucco Basin, Calabria-Peloritani Arc, Mass Transport Deposits, syn-tectonic sedimentation.

Geological mapping of the Longobucco Basin (NE Calabria) revealed the multifaceted nature of the Paludi Formation, an unconformity-bounded, syn-orogenic, turbiditic/megaclastic unit. Sedimentology and lithostratigraphy were merged with nannoplankton and macroforams analysis. The Longobucco Basin belongs to the Calabria Peloritani Arc, an exotic crustal fragment, scraped off from its original paleogeographic position along with other continental ribbons (Kabilie, Alboran, Rif) and accreted to the Apennines during the southeastwards retreat of the Adria-Ionian slab. The Longobucco Basin hosts a Meso-Cenozoic succession overlying the Hercynian basement, and it records polyphase deformation: i) two extensional phases in the Early Jurassic, related to opening of the W Tethys, ii) a compressive phase in the ?late Oligocene/early Miocene followed by a poorly constrained extensional event. The Mesozoic succession ends with Hauterivian Maiolica-like deposits and is unconformably overlain by the Paludi Fm, which exhibits three lithofacies: a) reddish marls and shales (“Scaglia” facies), b) turbiditic sandstones and hybrid arenites, and c) clast- to matrix-supported breccias. The reddish marls are locally cannibalized by megaclastic and turbiditic deposits. Lithofacies (c) includes two mass transport deposits (MTD), >100m thick in the depocentres and with a lateral continuity of 6km. The basal megaclastic interval rests on the basement through a basin-wide SW-dipping onlap surface. Lithofacies (b) bears chaotic intervals, slumped megabeds to debrites, and calcarenites/hybrid arenites bearing macroforams in the form of resedimented loose grains forming biostratigraphically coherent assemblages, suggesting they are penecontemporaneous with the turbidites and thus provide reliable ages. Nannoplankton from the hemipelagites served for cross-checking the ages derived from benthic forams. Both methods produced an early Eocene age (Ypresian) for the basal Paludi and a late Oligocene/?Aquitania age for the top.

The style of basal interaction of the MTD with the substrate varies, with two main modes: i) deep plastic deformation of the substrate paired with sand injections, and ii) erosion, with scours and grooves. Clasts pertain to the Mesozoic succession or to the basement (phyllites, granitoids), ranging in size from pebbles to megablocks (longer axis up to 220m). Semi-consolidated clasts and bedstacks display common ductile/brittle features (asymmetric rootless folds, pseudo sigma structures, boudinage, shear zones). As sedimentation of the Paludi Fm is mainly the product of mass wasting processes, the unit as a whole can be referred to as a Mass Transport Complex.

Clast composition, paired with biostratigraphic ages, suggests the Paludi Fm was sedimented in a foredeep setting, receiving the products of the dismantling of an Alpine orogen. This was followed by shortening during a proto-Apenninic phase, and eventually by accretion to the Apenninic orogen.



## **Formation, dissolution and fluvial incision of the top evaporite seismic unit (Nahr Menashe) recording the end of the Messinian salinity Crisis , NE offshore Levant Basin, Eastern Mediterranean**

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*Keywords:* Messinian salinity crisis, seismic facies, dissolution, evaporite, passive infill, Levantine Basin.

Over the last decade, there has been a resurgence of interest in the climatic and tectonic mechanisms that drove the Messinian salinity crisis (MSC) and the associated deposition of thick evaporites. The MSC represents an unprecedented palaeoceanographic change that led to a very short (c. 630 kyr) ecological and environmental crisis (Andreetto et al., 2021). However, across the Levantine offshore basin, the sedimentological nature of the top evaporitic units and the mechanisms that controlled the transition from a hypersaline evaporitic unit to brackish deposits (final MSC stage 3) are still disputed. Here, we re-evaluate the deposits associated with the terminal phase of the MSC (ca. later stage of 3.2 by Meilijson et al., 2019), named in offshore Lebanon as the Nahr Menashe deposits (NM, Madof et al., 2019). We describe the NM seismic facies, characterize and map its internal seismic stratigraphy, and provide a new interpretation of its depositional environment, which persisted during the late Messinian and then evolved through a regional reflooding event. The base of the NM and some of its internal units overlies semi-circular depressions, randomly distributed linear marks and surface collapse features, which are indicative of a period of intense evaporite dissolution. The NMU seismic facies observed from the slope to the deep part of the basin support the interpretation of a layered salt-evaporite-sand depositional system subject to complex reworking, dissolution, deposition, and final erosion. A drainage network of valleys and complex tributary channels incising into the top NM shows marked erosional characteristics, which indicate a dominant southwards sediment transfer following deposition of the NM. This erosional drainage network formed due to the base-level fall associated with the last phase of the MSC. The base of the channel/valley network does not cut below the bottom of the Nahr Menashe dissolution surfaces. The channel and valley network was subsequently infilled by layered sediments interpreted here to represent the post-MSC marine sediments deposited during reflooding. Our analysis points out that the NM may represent a mixed evaporite-siliciclastic affected by karstic processes, deposited or re-deposited in a shallow marine or lacustrine during the tilting of the offshore Lebanese basin. Only subsequently did the NM experience a rapid erosional event followed by swift burial of transgressive/high-stand sediments.

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## **Mineralogy and geochemistry of Bengal Fan turbidites (IODP 354): Himalayan provenance and depositional history**

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*Keywords:* Petrography, heavy minerals, provenance studies, diagenesis, Bengal Fan, turbiditic sediments.

The terrigenous sediments of the Bengal deep-sea fan (Indian Ocean) represent an archive of Himalayan source-to-sink processes. Mineralogical and geochemical data on silt- and sand-sized sediments of the Bengal Fan turbiditic depositional system allow us to unravel their provenance, to discriminate between pre-depositional and post-depositional processes controlling sediment mineralogy, and to link their depositional history to uplift and erosion of different tectono-stratigraphic Himalayan domains.

The IODP Expedition 354 to ~8°N in the Bay of Bengal drilled seven sites along a 320 km transect across the Fan thus providing a spatial overview of the turbiditic depositional system. A complete section of the fan and pre-fan deposits was recovered at the deep-penetration U1451 drill site. Eighteen samples from the shallow drill site U1454 and two deep-penetration drill sites U1450 and U1451 collected down to a depth of 1200 m were analysed, together with four additional samples from drill site U1444 collected during IODP Expedition 353.

The mineralogical and geochemical variability among different samples, both collected at different depths within the same core (intra-core) and among cores (inter-core) was investigated. Intra-core mineralogical variability provides information about provenance changes and/or diagenetic effects, whereas inter-core variability helps us to check for potential differences associated with lateral shifts of dispersal patterns through time. The intensity of mineral dissolution in silt versus sand samples will also be analysed to verify whether least stable minerals are prone to be preserved better in less permeable mud-rich layers.

In Pleistocene sediments down to 400 m below sea floor, rich heavy-mineral suites include hornblende, epidote and garnet, with subordinate apatite, clinopyroxene, tourmaline, sillimanite, kyanite, zircon, titanite, and rare staurolite and rutile. In Pliocene-Miocene sediments, the heavy mineral concentration decreases, and assemblages are relatively enriched in garnet and epidote at the expense of amphibole. The relative abundance of zircon, tourmaline, and apatite increase progressively in older strata.

Mineralogical and geochemical compositions testify to long-distance provenance from the Himalayan Range via the Ganga-Brahmaputra fluvio-deltaic-turbiditic system and confirm that the Bengal Fan was a major sink for Himalaya-derived material since the Miocene. Petrographic and mineralogical data, combined with biostratigraphic, paleomagnetic, and geochemical evidence, allow us to unravel the sedimentary history of the Bengal Fan as related to Himalayan uplift, erosion, and monsoon development during the last 10 Ma.

## Coarse-grained deltas approaching shallow-water canyon heads: A case study from the Lower Pleistocene Messina Strait, Southern Italy

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*Keywords:* canyon-head deltas, cyclic steps and antidunes, Lower Pleistocene, Messina Strait, tidal dunes, tidal strait.

The tide-dominated Messina Strait (southern Italy) is a 3 km wide marine passageway, whose block-faulted borders form steep subaqueous zones incised by canyons and gullies. These erosional features retreat towards the shorelines and are often in direct connection with subaerial valley-bounded river deltas. High-energy density-flows generated by river floods periodically enter the canyon heads, attaining supercritical-flow regime and accreting large, upslope-migrating bedforms. Although these bedforms have been documented in recent studies, little attention has been paid to the definition of the type of delta entering canyon heads, the internal features of river-influenced deposits accumulated in the nearshore zone, and their interplay with tidal currents flowing axially to the strait. This study focuses on a Lower Pleistocene coarse-grained succession exposed along the north-eastern margin of the modern Messina Strait, investigated using conventional facies analysis and sedimentological logging, integrated with photogrammetric techniques and interpretation of drone-acquired imagery. Facies confinement between basement blocks suggests a subaqueous delta complex shed from the tectonically controlled margin of the ancient strait and entering shallowly submerged canyon heads. Basal breccias, conglomerates and pebbly sandstones exhibiting channel-form discontinuities and upslope dipping backsets are interpreted as cyclic-step and antidune deposits. Units composed of these facies are comprised between master erosional surfaces and tidal ravinement surfaces. The tidal ravinements suggest that canyon infill occurred during a major phase of sea-level rise, punctuated by minor falls and stillstands. These surfaces are overlain by mixed bioclastic–siliciclastic, arenitic, trough and planar cross-strata, representing dunes migrating roughly parallel to the palaeo-coastline and originated by tidal currents amplified by the narrowing of the ancient Messina Strait. Tidal-influenced sedimentation dominated over the fluvial-influenced processes during the late transgression, overflowing the canyon relief. The exceptionally good exposure of depositional architectures and facies characteristics is key to outline the general features of a specific type of delta system, fed by valley-bounded rivers and entering canyon heads in the nearshore of tectonically-controlled, tide-influenced steep strait margins. The pre-existing subaqueous incised topography forced the delta front to be split into lobe branches during the canyon infilling, hampering cliniform architectures and preserving large supercritical-flow sedimentary structures. This study suggests these as possible criteria for the recognition of similar systems in outcrop or subsurface.

## Nd isotopes support the role of subaerial LIP weathering and continental emergence for the rise of atmospheric O<sub>2</sub> during the GOE

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*Keywords:* Hamersley Basin, Weathering of subaerial continental land masses, Nd isotopes, Subaerial Large Igneous Provinces, Great Oxidation Event, Paleoproterozoic glaciations.

The Great Oxidation Event (GOE, 2.45 and 2.2 Ga) is a period during which oxygen raised permanently at appreciable concentration into Earth's atmosphere. One driving mechanism for the rise of atmospheric O<sub>2</sub> could be the emergence of continental landmasses and the increase of subaerial igneous province weathering. We tested this hypothesis in the Hamersley Basin of Western Australia because here the Turee Creek Group and the underlying Hamersley and Fortescue groups hosting the Woongarra, Weeli Wollie and Fortescue LIPs, form a continuous sedimentary sequence deposited between ~2.76 and 2.45 Ga. Here, we report Nd isotope composition of the different sedimentary rocks (shales, carbonates and glacial diamictites of the Meteorite Bore Member) forming the 2.45 to 2.1 Ga Turee Creek Group and underlying 2.45 Ga old Boolgeeda Iron Formation and associated glacial diamictites of the Hamersley Group.

In a mafic-felsic-weathering (MFW) diagram, BIFs, shales, glacial diamictites and carbonates overlap the Fortescue mafic/ultramafic and Woongarra felsic LIPs. In a  $\epsilon\text{Nd}(t)$  vs.  $147\text{Sm}/144\text{Nd}$  diagram, these sediments define two trends originating from a similar hydrothermal component but diverging towards two different subaerial continental reservoirs. One reservoir is radiogenic and is represented by the Fortescue LIP komatiites while the other one, similar to the present-day upper continental crust, is characterized by the crustally-contaminated basalts of the Fortescue LIPs and rhyolites of the Woongarra LIP. Additionally, Al-poor (< 1 wt.%) BIFs with seawater-like REY patterns and  $\epsilon\text{Nd}(t)$  values overlapping the LIPs reservoirs indicate that chemical weathering was also active during sediment deposition. Overall, we see a major shift in the Nd-isotopic composition in the Hamersley basin at ~ 2.45 Ga. This could reflect either a change in the sedimentary source because of the emplacement of the Woongarra Rhyolite and Weeli Wollie LIPs, or the change in the nature of fluid-rock interactions due to the drastic emergence of continental landmasses that would have exposed larger surfaces and different rock types to weathering, which collectively approximate the present-day continental crust. These results are further discussed in light of trace element and Nd isotope data available from other Archean-Paleoproterozoic basins worldwide.

## **Bottom current-controlled Quaternary sedimentation at the foot of the Malta Escarpment (Ionian Basin, Mediterranean)**

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*Keywords:* sediment waves, seismics, oceanography, cyclicity, Mediterranean.

A better understanding of the evolution of bottom current circulation and associated deposits is significant for many applications including paleoclimatology and geological hazard. Besides the large contourite drifts, bottom currents may generate fields of large sediment waves that, depending on their height and velocity of migration, may pose severe risk for infrastructures. Conversely, the time span of their paleoceanographic record is generally relatively short. We use bathymetry data, sub-bottom and seismic reflection profiles and legacy oceanographic data to analyse the sediment waves occurring in a deep environment (from 2400 to 3800 m water depth at the foot of the Malta Escarpment in the Mediterranean Sea) to understand their evolution in time, their significance for paleoceanography, and their relation to present day hydrographic conditions. In the absence of direct stratigraphic information, we use the information from nearby studies and from ODP Site 964 and DSDP Site 374 to constrain the age of the sedimentary successions. We discover that these waves (about 2.5 km in wavelength, 50 m in height, with crest sub-perpendicular to the continental slope trend) have been steadily growing and migrating northward since about 500 ka, although an irregular growth and unsteady migration is distinguishable since about 1,800 ka. The waves are generated by predominantly alongslope southward flowing bottom currents compatible with modern hydraulic conditions (mean flow speed of  $\sim 5$  cm  $s^{-1}$ , peaks of 15 cm  $s^{-1}$ ). The rate of crest migration ( $\sim 2.0$ -3.2 mm  $a^{-1}$ ) and the average sedimentation rate (0.64 - 0.69 mm  $a^{-1}$ ) are unusually high for deep sea environments away from turbidity currents paths. We infer that the steady development of sediment waves is produced by a drastic increase in sediment input to the Ionian Basin resulting from the tectonic uplift in NE Sicily and Calabria and the onset of a relatively steady, low energy bottom current regime following the Mid-Pleistocene Transition. We attempt to extract information on orbital cyclicity preserved in the seismic record from the power spectra of virtual seismic traces from the well preserved succession of 5 visually discernible, regularly spaced sub-units consisting of alternation of high-amplitude and low-reflectivity packages within the last 500 ka. Peaks in the power spectra can be identified around orbital obliquity and precession periodicities, while eccentricity appears not to be recorded. We discuss the results of seismic cyclicity analysis relative to uncertainties of stratigraphic and petrophysical constraints. The sediment waves along the foot of the Malta escarpment are an excellent candidate for the extraction of a long, continuous and high resolution sedimentary record of the paleo circulation changes and climate cycles in the Mediterranean Sea since about 500 ka.

## Late Quaternary glacial-interglacial cycles as revealed by the interfluve architecture of the Arno palaeovalley (Northern Tuscany, Italy)

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*Keywords:* glacial-interglacial cycles, interfluves, MIS 5e lagoon, Arno delta plain, late Quaternary.

Palaeovalley systems developed during the last glacial-interglacial cycle and now buried beneath modern delta-coastal plains occupy a central place in the debate about incised valley systems (IVSs) and sequence stratigraphy. However, the stratigraphy of Last Glacial Maximum (LGM) interfluvial areas has attracted little attention compared to the internal fills, because deprived of expanded fine-grained successions and affected by hiatal surfaces, physically represented by palaeosols. Despite remarkable stratigraphic condensation, interfluves are prone to preserve the depositional record of successive transgressive-regressive cycles, as they are not affected by deep river incisions, unless shifts in the valley axis through time. In this study, we analysed the late Quaternary stratigraphic architecture of the southern interfluve of the LGM Arno palaeovalley (Northern Tuscany, Italy) by means of facies-based stratigraphic correlations involving a wealth of sedimentary cores. Facies characterization benefitted from the analysis of the meiofauna (benthic foraminifers and ostracods) found within reference cores. Palynological data from one core supplied important information about vegetation-derived palaeoclimate conditions, supporting the <sup>14</sup>C-based chronological framework.

Above the laterally extensive LGM palaeosol, ~15 m below sea level (b.s.l.), a progradational stacking pattern of facies testifies the outbuilding of the delta system after the Holocene maximum marine ingressions. Below, down to ~40-50 m b.s.l., the interfluve architecture is typified by a few m-thick floodplain clays with closely-spaced palaeosols overlying a weakly pedogenised paludal-lagoon succession, superimposed via a further palaeosol on a tens m-thick alluvial succession, including thick, amalgamated fluvial-channel sands. Pollen (Mediterranean forest with increasing optimum-like conditions) points to a MIS 5e age for the lagoon deposits. On the other hand, alluvial intervals contain pollen assemblages indicative of an open/sparse pine forest typical of glacial periods, specifically the last glacial and the penultimate glacial.

Data integration along stratigraphic profiles allowed to: *i*) relate the MIS 5e lagoon to the inundation of an older interfluve associated laterally to a km-wide channel belt likely formed during the penultimate glacial period (MIS 6) and *ii*) furnish insights on the evolution of a coastal plain at the onset of glacial conditions, through its emersion and transformation in an interfluvial area subject to pedogenesis.

Our data suggest a very slowly subsiding setting for the southern portion of the Arno delta plain and, accordingly, highlight a complex stratigraphic architecture characterised by recurring channel incisions and interfluve development mainly controlled by glacio-eustatic oscillations.



## **Sedimentological and petrographic evolution of the Oligo-Miocene succession in the Carrosio and Arquata Scrivia area (eastern Tertiary Piedmont Basin, NW Italy)**

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*Keywords:* Tertiary Piedmont Basin, petrography, source-to-sink.

The Tertiary Piedmont Basin of NE Italy is an episutural basin which lies at the junction between the Alpine and Apennine chains. Its late Eocene to Pliocene sedimentary fill is thus important because it may provide a record of a source to sink system modulated by tectonics. This study focuses on sedimentology and petrography of the sedimentary succession cropping out in the Arquata Scrivia-Carrosio area, a key sector separating the Alto Monferrato area to the west from the Borbera-Curone sub-basin to the east.

The lithostratigraphic succession indicates initial establishment of a conglomeratic fan-delta (Conglomerati di Savignone and Molare Fms., Rupelian), which is drowned and overlapped by slope hemipelagic marlstone and channelized turbidites (Gremiasco Fm., Chattian). These are followed up section by a suite of confined turbidites, mass transport deposits, and channelized turbidites (Castagnola and Costa Montada Fms., Aquitanian-Early Burdigalian pro-parte), which record a further deepening culminating in the establishment of a basin plain environment (Costa Areaa Fm., Early Burdigalian-Langhian). Lastly, from the late Langhian onward, tectonic uplift resulted in a regional unconformity capped by shelfal marly deposits with storm layers and hyperpycnites (Marne di Cessole Fm., Langhian).

Quantitative petrographic analysis of the above succession allowed us to recognise 11 petrofacies, which were compared and contrasted in a stratigraphic perspective. In agreement with previous studies, we identified lithic fragments from the Voltri Group, the Sestri-Voltaggio Zone, the Ligurian Apennine Units and the Mortara Volcanic complex, which can be therefore regarded as the main sediment sources. Results show that quartz and feldspars fractions increase up-section, whereas that of lithics decreases. In the lithic fraction, a decrease in the content of metamorphic lithics is observed in favour of volcanic and sedimentary lithotypes.

The increase in quartz and feldspars content requires further investigation to be linked to candidate source terrains (Dora Maira? Cristallino di Valosio?). On the other hand, the increase of the volcanic fraction is partly coeval to the Mortara Volcanic complex (Upper Oligocene-Lower Miocene), now buried about 50 km to the north of the study area, and may thus correlate to an acme of volcanic activity and/or dismantling of its products. Lastly, the increase of the carbonate fraction can be interpreted to reflect the establishment of carbonate platforms of similar age documented at outcrop both to the N and S of the study area (P. da Cantoni Fm. of the Basso Monferrato and Visone Fm. of the Alto Monferrato, respectively) and in the subsurface (Quargnento High) to the N.



## **Facies analysis and depositional environment of a late Cambrian mixed carbonate-siliciclastic ramp from the Arabian Plate (Zagros Basin, Southwestern Iran)**

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*Keywords:* Early Palaeozoic, Zagros, Palaeogeography, Arabian Plate, Gondwana.

Early Palaeozoic represents a crucial period in Earth history, marked by intervals of life spread alternated with short-lasting crisis in biological activity. The Zagros Basin (SW Iran) could be a key area for the study of this time interval, due to the widespread and well-exposed Cambrian-Ordovician successions; nevertheless, these are still poorly constrained from a sedimentological and stratigraphic point of view. This study, carried out through a high-resolution facies and microfacies analysis of the Zard Kuh section, aims to give a contribution to the palaeogeographic evolution of this area. The studied section (296 m thick) includes the upper Mila C Member and Ilebeyk Formation, referred to the late Cambrian (Furongian) based on acritarch assemblages. The upper Mila C Member (23 m thick) is mainly characterized by medium to thin-bedded bioclastic packstones to mudstones grading upward into a nodular limestone unit. A sharp horizon marks the contact with the overlying Ilebeyk Formation, represented by a shale-dominated interval in the lower part. These mudrocks grade upward into heterolithic lithofacies, generating a coarsening upward sequence with an increase of siltstone and sandstone intercalations in the lower-middle part. The coarser-grained layers display scoured basal surfaces, with common gutter casts, capped by plane parallel lamination and hummocky cross-stratification (HCS). In the middle part of Ilebeyk Formation, siliciclastic deposits are alternated with relatively thick carbonatic intervals, showing similar features with Mila C Member. The upper part of the Ilebeyk Formation is dominated by shales, overlain at the topmost by a 28 m thick unit of micaceous sandstone and siltstone. The sandstone layers include plane-parallel bedding, trough cross-stratification and long-wavelength HCS. Based on the facies and microfacies analysis, the depositional system of the studied section is interpreted as a mixed carbonate-siliciclastic ramp. In the Mila C Member and carbonatic unit of Ilebeyk Formation, small cycles characterized by erosive surfaces and fining upward fossiliferous biomicrites suggest deposition in middle ramp setting, affected by storm events. On the other hand, the nodular limestone intervals at the top of the carbonatic units point to deposition below the SWB under a transgressive regime. The shale to heterolithic parasequences from the Ilebeyk Formation are interpreted as autocyclic fluctuations of the depositional system from lower to upper offshore environment. In the uppermost part, the sandstone-dominated interval is attributed to shoreface setting, marking an abrupt change in the bathymetric conditions after a forced regression. The sedimentological features of the studied area can be correlated with other coeval depositional events at both regional (Arabian plate) and global (Laurentia and Baltica) scales, providing new constraints for the lower Palaeozoic evolution of the northeastern Gondwanan margin.

## The Provenance of Modern Sands from Baja California Rivers (Mexico): Petrographic Constraints from Light and Heavy Minerals

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*Keywords:* volcanoclastic sand, Baja California, heavy minerals.

Modern sand composition of three rivers, reflects the nature of the source region, which lies in the central part of the Alisitos arc (Peninsular Ranges, Baja California, Mexico). The sand detrital modes correspond well with the main structural units drained by El Rosario, San Fernando, and San Vicente rivers: (1) the Early Cretaceous oceanic arc of the Alisitos Group, (2) the Paleozoic to Mesozoic continental margin metasedimentary rocks, (3) the Cretaceous plutons, (4) the Late Cretaceous to Tertiary sedimentary rocks, and (5) the Tertiary volcanics. San Vicente, San Fernando, and El Rosario are chiefly fed from erosion of a magmatic arc in various stages of dissection and mostly consist of minor feldspatho-lithic (Fl) to quartzo-litho-feldspathic (qFL) sand and dominant quartzo-feldspatho-lithic (qLF) and litho-feldspatho-quartzose (IQF) sand. Increasing degree of dissection is indicated by progressive increase in quartz, K-feldspar, sedimentary and metamorphic, and decreasing of volcanic lithic fragments. Sand, within the Lv field, microlitic (Lvmi), contains felsitic (Lvf), and lathwork (Lvl) types, and trace amounts of vitric grains (Lvv), such as pumice particles. Andesitic volcanic province of the Alisitos arc shed quartz-poor sand containing mainly microlitic lithic fragments and plagioclase, sand derived from more felsic rhyolites and rhyodacitic and trachyandesitic products contains largely felsitic volcanic lithics whereas minor lathwork lithics are mainly derived from subordinate basalts. The abundance of igneous rock fragments and volcanic and sedimentary lithics of the three studied rivers sand faithfully represents the relative abundance of a heterogeneous [volcanic+plutonic+sedimentary] bedrock exposure in each drainage basin. In the medium to fine sand of the drainage systems, the transparent heavy minerals suite includes mainly hornblende, pyroxene, epidote, titanite and zircon, and minor quantities of staurolite, rutile and garnet. Other heavy detrital species identified in the San Fernando and San Vicente river sand are tourmaline, sillimanite, kyanite and andalusite. Unstable heavy minerals (Amphibole, Pyroxene and Apatite) predominate in El Rosario River compared to San Fernando and San Vicente rivers sand that are enriched in the moderately stable species such as epidote, kyanite and sillimanite. Hornblende and pyroxene grains show mainly corroded to etched morphologies due to dissolution processes whereas epidote remains unaltered. Pyroxene grains are more corroded than amphiboles. Sedimentary recycling produced subrounded to rounded in zircon grains in the San Fernando river sand. Also, sand composition typified by the heavy minerals reflect provenance from multiple and differently weathered sources. Specifically, San Fernando and San Vicente river abundance and weathering textures of the heavy minerals match predominant sedimentary and metasedimentary bedrock lithologies and El Rosario volcanic source rocks.

## **Facies modelling of proximal environment in the upper Tortonian-lower Messinian carbonate ramp of Hyblean domain (Faro Santa Croce, Sicily, Central Mediterranean)**

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*Keywords:* 3D digital modelling, late Miocene, facies mosaic, seagrass, outcrop analogue, photogrammetry.

This work illustrates a combined modelling approach using digital photogrammetry and geological modelling to create a high detailed 3D facies model of the inner environment of the Monte Carrubba carbonate ramp outcropping in the South Sicily. The Monte Carrubba Formation is the youngest marine Miocene carbonate deposit of the Hyblean region, prior to the Messinian crisis of the Mediterranean. In particular, Faro Santa Croce outcrop shows the most proximal sector of this ramp. The Faro Santa Croce outcrop offers the opportunity to investigate and reproduce a highly-detailed facies heterogeneity 3D model for a very narrow and limited area of few squared kilometers, developed in a tectonically stable area. Within this small areal, five facies have been recognized and modelled revealing a high level of facies heterogeneity. In this area marine ooidal shoals (ooidal grainstone to packstone) interfingered with shallow water seagrass environment (green-algal-floatstone facies and bioclastic grainstone-to-packstone) with abundant mollusc fauna. The distal part of this vegetated environment (fine mollusc-packstone facies) pass basinward into coral mounds (coral boundstone).

The combination of digital photogrammetry and 3D geological modelling software has allowed to obtain a very high-resolution model of facies heterogeneity, evidencing the complexity of facies associations and, in particular, the development of a facies mosaic that can be underestimated by a classical 1D or 2D field analysis, especially in limitedly-exposed outcrops.

## **Petrology and distribution of the Miocene-Pliocene gravel size clasts from IODP\_exp374 Site U1522 drillcore in the Ross Sea (Antarctica)**

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*Keywords:* International Ocean Discovery Program, Site U1522, Antarctica, provenance, glaciogenic sediments, clast petrology, Ross Sea, WAIS.

The International Ocean Discovery Program (IODP) Expedition 374 aims to investigate the interactions between water masses and ice sheets in the Ross Sea (Antarctica) to resolve Neogene and Quaternary relationships between climatic forcing, oceanic changes and West Antarctic Ice Sheet (WAIS) evolution during the past. Five sites in the continental shelf to rise of the central Ross Sea region were drilled during the 2018 austral summer. Site U1522 is located in the Glomar Challenger Basin and was cored to 701.8 meters below seafloor (mbsf), recovering ca. 280 m of upper Miocene to Pleistocene glacial marine sediments.

We analyzed in continuum the Miocene-Pliocene section of the cores, logging and describing every gravel size clast (> 2mm), which we categorized by lithology into 9 groups (intrusive rocks, quartz fragments, basaltic rocks, dolerite, metamorphic rocks, sedimentary rocks, felsic porphyries, and mud intraclasts). Moreover, 40 pebbles and cobbles were sampled for the petrographic characterization in thin section from the upper Miocene interval of the site (between ca. 700 and 490 mbsf). The most common logged lithologies are low- to medium-grade metamorphic rocks, which are mainly biotite ± white mica meta-sandstones, schists, and gneisses; felsic, and minor mafic, intrusive rocks and porphyries are present in lower numbers. Basaltic rocks are widespread along the cores, whereas dolerite clasts are rare in the depositional record. A major change of clast lithology assemblage occurs below the Miocene-Pliocene boundary, where a percentage decrease of intrusive and basaltic rocks, associated with an increase of metamorphic ones and minor of dolerite, is recorded. Above the regional scale Ross Sea Unconformity 3 (RSU3) a percentage increase of intrusive clasts is also recorded. These changes could reflect shifting sediment supply in response to a new WAIS configuration.

## Architecture of fault-controlled Norian intraplateau basins (Southern Alps, Italy): geometry and possible mechanisms of a rift cluster

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*Keywords:* Norian, rifting, extensional regime, intraplateau basins, master faults, transfer faults.

The Norian (Late Triassic) extensional regime that preceded the Jurassic rifting led to the identification of numerous fault-controlled intraplateau basins, segmenting and dismembering the carbonate inner platform of the Dolomia Principale, which during the Norian age extended from Hungary to Central Italy, including the Southern Alps.

In the Central Southern Alps (Lombard Basin), the Norian rifting is documented by numerous faults with normal throw, dislocated sometimes by transfer faults.

The Norian tectonic regime led to the definition of a set of roughly aligned intraplateau basins, varying in size from a few km<sup>2</sup> up to about 100 km<sup>2</sup>. The paleogeographic picture of the Norian allows us to observe how these intraplateau basins are located both in the central sector of the Lombard Basin (e.g., Aralalta Basin), and in the easternmost one, between Iseo and Garda Lake (e.g. Magasa –Capovalle Basin). The intraplateau basins are interpreted as asymmetrical semi-graben delimited by fault escarpments (master-fault) on one side.

The Lombardy basin is bordered to the west by the high of the Canavese area and to the east by the Trento High. It can be divided in two areas separated by the Val Sabbia Fault: the eastern one between Garda Lake (Ballino Garda Line) and Idro Lake and the western one between Val Sabbia and Brembana Valley.

In the eastern area, basins (e.g. Magasa-Capovalle Basin) were characterized by extensional faults with NE-SW direction displaced by strike-slip faults (possible transfer-fault) with E-W orientation.

In the western area the basins (e.g. Lumezzane, Alone and Nave basins) are delimited by transtensive faults in an E-W direction (only the Nave basin is delimited by approximately N-S faults). The extensional master faults are generally developed on the western side of the asymmetrical basins.

The distribution of the Norian intraplateau basins in the Southern Alps defines a rift cluster, with faults belonging to two systems with different present-day orientation. The existence of these two sets that seem to control the development of basins with different structural directions (roughly E-W and NE-SW in the western and eastern sectors, respectively) can be explained with three causes: i) Norian transtensional tectonics, with two conjugated fault systems; ii) post-genetic anticlockwise rotation of fault-bordered blocks during the Alpine orogenesis that affected the structural corridor between Idro and Garda lakes; iii) existence of two different Norian events, with different stress fields.

No undisputable evidence supporting one of these three possible causes is clearly available: at the moment the three hypotheses are all acceptable. Anyway, the presence of basins with differently oriented faulted may suggest a possible origin related to conjugated transtensional fault systems that acted during the Norian, in the initial phases of the Mesozoic rifting.

## Detrital modes of Permian sandstones in southern Italy

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*Keywords:* Permian, sandstone composition, Puglia 1 Well, Sosio Valley, Sicily.

During Permian, the Pangea supercontinent experienced the most critical and dramatic restocking of its configuration. Meanwhile, in the Mediterranean region, the occurrence of late Paleozoic siliciclastic strata experienced peculiar tectonic and climatic environment. Here, we detail the Permian sedimentary succession types displayed in some portions of the circum-Mediterranean region, providing new insights about the composition of Permian siliciclastic strata of the basal Apulian Unit, in Puglia 1 well log, and the Sosio Valley succession in Sicily. Permian sandstones, and related mudrocks, record a synchronously phase of post-Variscan collision and subsequent final closure of Paleotethyan ocean. Sedimentological and stratigraphic framework, also associated to the distribution of mineralogical composition of sandstones and mudrocks, are pivotal factors to reconstruct the sedimentary evolution of the Permian paleogeography.

The Apulia Unit played a critical role because it stood relatively still in the Mediterranean paleogeographical contest and received a great Permian sedimentary load. Nowadays these strata were intersected in Puglia 1 well between 7070 m to 6110 m in depth, for 960 m in thickness, with sandstone, mudstone and breccia mostly. Meanwhile a Sicily Permian succession (the San Calogero Formation) is well preserved, outcropping around the Sosio Valley (northwestern Sicily), by few tens of meters of marine sandstones and clays strata.

Sandstones of the Puglia 1 Well are quartzolitic, with abundance of quartz and metasedimentary lithic fragments (mainly phyllite and schist). Feldspars are minor. Sandstones of the San Calogero Fm. in Sicily, are more variable in composition, from quartz-rich sandstone, to hybrid arenites and calcilithite, and include abundant extrabasinal carbonate fragments and metasedimentary lithic fragments, as such as important contributions of intrabasinal carbonate grains. Interbedded volcanic and volcanoclastic layers are also present.

These siliciclastic strata experienced a diverse burial history. The Puglia 1 succession presents moderate carbonate cements, that are dominant, and consist of crystals of dolomite, ankerite and calcite (related to dedolomitization/calcitization processes of the first carbonates. Mudrocks display K-enrichments, intense paleoweathering under a hot, episodically humid, climate with a prolonged dry season, and sediment recycling processes. Meanwhile Sicily succession is pervaded by carbonatic poikilotopic cements mostly, siliciclastic matrix and less iron cements. Quartz overgrowths are locally present.

In terms of provenance, sandstone detrital modes are typical of quartzolitic sandstones, hybrid arenite and calcilithite: that should be related to the erosion of upper crustal levels of the Variscan orogenic terranes, with most of metasedimentary and sedimentary rocks occurring in Calabria-Peloritani, southern Alps and in internal domains of the Circum-Mediterranean orogens.

## **Reactivation or non-reactivation? Analogue models of multiphase rifting and applications to the Turkana depression, East Africa**

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*Keywords:* Turkana depression, tectonic basin, fault reactivation, analogue models.

The Turkana depression (Ethiopia-Kenya) is a tectonic basin related to the Cretaceous-Early Cenozoic development of the South Sudan and the Anza grabens filled with a thick sequence of Cretaceous-Paleogene sediments reaching up to a thickness of 6–8 km. These two NW-SE trending depressions, which likely resulted from NE-SW extension, were later affected by W-E extension related to the Cenozoic East African Rift System. The influence of crustal thinning related to these NW-SE grabens on later W-E-related extension is testified by the marked change in style of deformation from the narrow rift valleys in Kenya and Ethiopia, to a distributed, basin-and-range-style faulting in the Turkana depression. Despite some local scale reactivation is visible, large scale reactivation of pre-existing NW-SE structures in the Turkana depression is not obvious, as it is extensively masked by the sedimentary and volcanic cover; consequently, contrasting hypothesis on the possible role exerted by discrete pre-existing fabrics have been proposed in the literature.

To address this controversy, we performed analogue models to investigate whether inherited structures, largely obscured by sediments in the Turkana depression, might have been reactivated during subsequent tectonic phases. We run 2-layer, brittle-ductile models deformed in two successive phases: a first phase of NE-SW extension, followed by W-E extension. Different models were subjected to different amount of bulk extension during the first phase to investigate the influence of this parameter (and the importance of first-phase structures) on later reactivation. Our models indicate that the amount of deformation in the initial tectonic phase is key for structure reactivation in subsequent tectonic phases: the larger the deformation in the first phase, the higher the probability of reactivation. Comparison of the experimental results with nature suggest that, despite some local fault reactivation, large-scale structures were likely not reactivated in the Turkana depression. These outcomes represent a useful tool to decipher fault reactivation, not only in the Turkana depression but also in tectonic basins worldwide, especially where thick sedimentary covers may mask tectonic structures.



**S3.**  
**Oceanic lithosphere and subduction factory**

*CONVENERS AND CHAIRPERSONS*

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## High velocity friction experiments on IODP materials: insights on earthquake propagation in the subduction zone

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Keywords: IODP, earthquake, experiments, mechanics.

International Ocean Drilling Projects provide a unique occasion to sample the materials transported into the subduction zone which control the subduction zone mechanics. In subduction zones a variety of slip styles may occur, depending on tectonic loading, on sediments permeability and frictional stability. Slip events can range from stable sliding aseismic creep, to unstable sliding in the form of either slow slip events or fast dynamic ruptures during earthquakes.

Friction experiments with rotary shear machines can provide insight in the mechanical behavior of sediments at the fast dynamic conditions expected during earthquakes. SHIVA, a state-of-the-art rotary machine (INGV, Rome), can apply the boundary conditions expected during earthquakes in the subduction zone at shallow depth in terms of: normal stress (<25 MPa), fault slip (several meters), slip rate (1-10 m/s) and acceleration (< 20 m/s<sup>2</sup>). Moreover, recent technological developments allowed for the first time the effective confinement of saturated and pressurized non cohesive sediments while at the same time imposing earthquake deformation conditions. Sediments undergo dynamic weakening, induced by temperature and/or pore pressure increase, which results in the decrease of strength and therefore a decrease in the level of sustainable shear stress the material can sustain.

In the recent years, natural materials sampled by IODP expeditions from Costa Rica, Sumatra Andaman, Hikurangi subduction zones were experimentally tested. Under variable degrees of hydration, these experiments provide a means of comparing materials between (or within) the different subduction zones in terms of: i) how fast weakening occurs, or ii) how much energy is being dissipated with respect to the possible energy stored in the fault rocks, or iii) if and how stress build-up can affect the subsequent earthquake slip. This allow us to hypothesize how earthquake propagation could be easier in a lithology under a specific hydration state (Vannucchi et al., 2017). Moreover, the experiments constrain the physical processes controlling fault weakening thanks to direct measurements of temperature, pressure and shear stress (Aretusini et al., 2021). Finally, these experiments provide a parametric basis for modelling the earthquake propagation during megathrust earthquakes (Murphy et al., 2018).

Aretusini S., Meneghini F., Spagnuolo E., Harbord C.W. & Di Toro G. (2021) - Fluid pressurisation and earthquake propagation in the Hikurangi subduction zone. *Nature Communications*, 12(1), 1-8.

Murphy S., Di Toro G., Romano F., Scala A., Lorito S., Spagnuolo E., Aretusini S., Festa G., Piatanesi A. & Nielsen S. (2018) - Tsunamigenic earthquake simulations using experimentally derived friction laws. *Earth and Planetary Science Letters*, 486, 155-165.

Vannucchi P., Spagnuolo E., Aretusini S., Di Toro G., Ujiie K., Tsutsumi A. & Nielsen S. (2017) - Past seismic slip-to-the-trench recorded in Central America megathrust. *Nature Geoscience*, 10(12), 935-940.

## **The western Durkan Complex (Makran Accretionary Prism, SE Iran): A Late Cretaceous tectonically disrupted seamounts chain and its role in controlling deformation style**

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*Keywords:* tectonically disrupted seamounts, Makran, Late Cretaceous, Iran, Neo-Tethys.

The subduction complexes develop at convergent plate boundaries and their architecture and the prevalent operating tectonic processes (e.g., accretion vs. erosion) are dependent on several factors. Among others, the occurrence of topographic reliefs along the subducting plates, such as oceanic seamounts, is believed to play a significant role in controlling the dynamic and the architecture of the frontal wedge. Studies of fossil accretionary complexes showing accreted seamounts can thus provide significant constraints to understand how the physiography of the subducting plate controls the tectonic evolution of the subduction complexes.

The Durkan Complex is a key tectonic element of the Makran Accretionary Prism (southeast of Iran) and it was interpreted as representing a continental margin succession (Hunziker et al., 2015). We present here a multidisciplinary study of the western Durkan Complex, which is based on new geological, stratigraphic, biostratigraphic data, as well as geochemical data of the volcanic rocks forming this complex. The new data show that this complex consists of distinct tectonic slices showing deformed successions recording volcanic activity and sedimentation in a seamount setting. Stratigraphic and biostratigraphic data allow us to recognize three types of successions. Type-I is composed of a Coniacian – early Campanian pelagic succession with intercalation of pillow lavas and minor volcanoclastic rocks recording the deep-water stages of growth of a seamount. Type-II succession includes a volcanic sequence passing to a volcano-sedimentary sequence with Cenomanian pelagic limestones, followed by a hemipelagic sequence. This succession is characterized by abundant mass-transport deposits. Type-III succession includes volcanic and volcano-sedimentary sequences, which are stratigraphically covered by a Cenomanian platform succession. Type-II and Type-III successions record volcanism and deposition along the flank and the summit of an emerged seamount. Differently from the interpretations so far proposed for the Durkan Complex, these results indicate that the western Durkan Complex represents fragments of oceanic seamounts tectonically incorporated in the Makran Accretionary Prism during the latest Late Cretaceous – Paleocene. The incorporation of Durkan seamounts in the frontal prism likely caused a shortening of the whole convergent margin and possibly controlled the deformation style in the Makran Accretionary Prism during Late Cretaceous–Paleocene times. These results further confirm that the physiography of the subducting plates plays a significant role for the tectonic evolution of the subduction complexes.

Hunziker D., Burg J.-P., Bouilhol P. & von Quadt A. (2015) - Jurassic rifting at the Eurasian Tethys margin: Geochemical and geochronological constraints from granitoids of North Makran, southeastern Iran. *Tectonics* 34, 571-593. <https://doi.org/10.1002/2014TC003768>.

## Structural and metamorphic evolution of the Rocca Canavese Thrust Sheet Unit (Sesia-Lanzo Zone, Western Alps, Italy)

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Keywords: Sesia-Lanzo Zone, Western Alps, structural analysis

In the geological setting of the Italian Western Alps, the Rocca Canavese Thrust Sheet Unit (RCT) is a small unit (only a few km<sup>2</sup>) marking the innermost sector of the Sesia-Lanzo Zone of the Austroalpine Domain, between the Eclogitic Micaschists Complex to the west and the Canavese Zone of the Southern Alpine Domain to the east. This unit has been described for the first time by Pognante (1989) as a series of thin thrust sheets made by pre-Alpine continental crust and upper mantle, separated by blueschists facies mylonites. Recently, the RCT has been referred to as a subducted-related *mélange* (Roda et al., 2018, 2019). This contribution presents new data on the structural and metamorphic evolution of the RCT. This unit is mainly made of ultramafic, mafic and metasedimentary rocks. Serpentine crops out in the easternmost part of the unit in contact with orthoglaucophanite and metasediment, and embeds plurimetric bodies of metagabbro. Orthoglaucophanite consists of massive to gneissic rocks in contact with metasediment and serpentinite. Metasediments have significant compositional variations from pelitic/felsic (micaschist and gneiss) to mafic (Wm-rich glaucophanite). Moving to the boundary with the Canavese Zone, laterally discontinuous masses of mylonitic orthogneiss occur within serpentinite. Five tectono-metamorphic events have been recognized. The first event is recorded by a relict foliation preserved in microlithons or as introfolial folds, and whose mineralogical association (Wm+Lws+Gln in metasediment and orthoglaucophanite) is typical of Lws-blueschists facies conditions. The second event marks the eclogitic peak of the RCT because it is defined by the assemblage Jd/Omp+Grt (metasediment, orthoglaucophanite and metagabbro) and by millimetric Omp-veins (orthoglaucophanite). The third event is responsible for the development of a very pervasive transpositive foliation defined by Wm+Gln+Ep s.s. assemblages (metasediment and orthoglaucophanite), recording Ep-blueschists facies conditions. This event led to the formation of millimetric Omp+Chl+Ep s.s. veins in metagabbro. A general late retrogression under greenschists-facies conditions is recorded by the last two stages defined in this study: the former develops crenulation cleavage in serpentinite and open to close folds in the other lithologies; the latter is characterized by Pl+Chl millimetric to pluricentimetric veins in metasediment and orthoglaucophanite.

Pognante U. (1989) - Lawsonite, blueschist and eclogite formation in the southern Sesia Zone (Western Alps, Italy). *Eur. J. Mineral.*, 1, 89-104.

Roda M., De Salvo F., Zucali M. & Spalla M.I. (2018) - Structural and metamorphic evolution of a tectonic mixing: is Rocca Canavese Thrust Sheet (Italian Western Alps) a subduction-related *mélange*? *Ital. J. Geosci.*, 137, 311-329.

Roda M., Zucali M., Regorda A. & Spalla M.I. (2019) - Formation and evolution of a subduction-related *mélange*: The example of the Rocca Canavese Thrust Sheets (Western Alps). *GSA Bulletin* (2020), 132, (3-4), 884-896.

## **In situ boron isotopes in ophicarbonates: implications for the B and C cycles in subduction zones**

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**Keywords:** Ophicarbonates, Boron isotopes, LA-MC-ICP-MS.

The subduction of ophicarbonates (*i.e.*, carbonated serpentinites) allows the transfer of volatiles (*i.e.*, water and CO<sub>2</sub>) acquired at surficial levels into the deep mantle, thus playing a pivotal role in their recycling in subduction zone settings at geological timescales. To date, the geochemistry of ophicarbonates has been often limited to the C-O isotopic signatures of carbonates and poorly is known about the elements hosted in the serpentine minerals that might provide further information concerning the oceanic genesis and the subduction evolution of ophicarbonates. Among trace elements that still deserve to be investigated in ophicarbonates, boron (B) is undoubtedly the most promising isotopic systematic. In fact, serpentine minerals are strongly enriched in B and their B isotopic signature is a powerful tracer of fluid-rock interactions. Currently, serpentinites from oceanic derivation are characterized by positive B isotope composition (expressed as  $\delta^{11}\text{B}$ ), from +5‰ and approaching seawater value (+39.6‰). In contrast, serpentinites from wedge-derived setting commonly show negative  $\delta^{11}\text{B}$  signatures, reflecting interaction with slab-derived and <sup>11</sup>B-depleted fluids. Data on the B isotopic signature of ophicarbonates are still lacking.

In this contribution, we present for the first time *in situ* B isotope measurements in serpentines from ophicarbonates with the aim to better unravel ophicarbonates evolution from oceanic to subduction settings. Samples are from the Alpine-Apennine ophiolite sequence representing a wide range of *P-T* conditions. The petrographic features of these rocks are extensively reported in previous works (Cannaò et al., 2020) together with their whole-rock and *in situ* geochemistry coupled with C-O and Sr isotopic signatures of carbonates. Boron isotopes were determined using the recent installed LA-MC-ICP-MS instrument at the Earth Science Department (University of Milano). Our data highlight how hydrothermal processes may have a strong impact in the evolution of the B isotope systematic in ophicarbonates, thus influencing the B budget of these rocks entering and evolving in convergent margins. As serpentinites highly govern the H<sub>2</sub>O budgets of subducting materials, the fluids released during the antigorite breakdown at high-*P* in ophicarbonates will also control dissolution of carbonates allowing C mobilization that may significantly impacts on the global C cycle.

Cannaò E., Scambelluri M., Bebout G.E., Agostini S., Pettke T., Godard M. & Crispini L. (2020) - Ophicarbonate evolution from seafloor to subduction and implications for deep-Earth C cycling. *Chemical Geology*, 546, 119626.

## Oblique exhumation of HP rocks at the southern tip of the Western Alps: a review

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Keywords: Ligurian Alps, Voltri Massif, exhumation, transpression, non-coaxial.

The exhumation of high-pressure terrains is a fundamental process that allows us to directly investigate the output materials of the subduction factory and therefore to study the transformations that the input materials undergo during their long path down to the mantle and back to the surface.

However, the exhumation process may obliterate peak-related structures and metamorphic associations at different degrees. In the Western Alps, one of the most studied orogen of the world, some HP terrains still preserve an almost complete stratigraphy of the oceanic lithosphere (e.g., the Monviso and Zermatt-Saas Massifs).

On the contrary, the HP rocks of the Voltri Massif and adjoining oceanic units, which crops out at the southern termination of the Alpine orogen, are at places characterized by a high degree of disruption of the original stratigraphy.

The Voltri Massif can be divided into two sectors: in the eastern one, the high-pressure eclogitic-blueschist rocks are frequently embedded as bodies and lenses within serpentinite or metasediments, which act as a low strength "matrix" that accommodates most of the strain. This has led to the interpretation of the Voltri Massif as a tectonic mélange, formed inside the subduction channel (Federico et al., 2007).

The western sector, on the contrary, contains relics of disrupted mélange associated to more coherent slices of metamorphic oceanic lithosphere.

From the structural point of view, the eastern sector is characterized by a steeply dipping foliation, steeply dipping blueschist to greenschist stretching lineation, high shear strain and prevalent structures typical of non-coaxial flow (Capponi and Crispini 2002). These structures are formed during a progressive evolution from blueschist to greenschist facies and are therefore related to the exhumation stage.

On the contrary, the western side of the Massif is characterized by shallow-dipping fabrics and prevalent structures dominated by flattening. Here HP -structures are better preserved and the greenschist-facies overprint is less pervasive and static at places.

Combination of new and reviewed structural data collected during several decades of fieldwork, geological mapping, PT-paths and geochronological data points to a model of exhumation in which a non-coaxial transpressional zone acted a fundamental role. Important rotation probably occurred at this stage, since the eastern high-strain zone is now perpendicular to the main orogen strike. This is likely due to the peculiar geodynamic position of the Voltri Massif, at the tip of the alpine subduction zone and to the interference with the embryonic Apennine-related deformation events.

Capponi G. & Crispini L. (2002) - Structural and metamorphic signature of alpine tectonics in the Voltri massif (Ligurian Alps, North-Western Italy). *Eclogae Geologicae Helvetiae*, 95(1), 31-42.

Federico L., Crispini L., Scambelluri M., Capponi G. (2007) - Ophiolite mélange zone records exhumation in a fossil subduction channel *Geology*, 35(6), 499-502; <https://doi.org/10.1130/G23190A.1>.

## The Bogota pyroxenites (New Caledonia): new insights on mantle heterogeneity in young subduction systems

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Keywords: pyroxenites, fore-arc mantle.

This contribution deals with a comprehensive petrological and geochemical investigation of a new set of subduction-related mantle pyroxenites from the New Caledonia ophiolite. We have investigated pyroxenite layers enclosed in refractory mylonitic harzburgites from the Bogota peninsula shear zone, which records HT deformation along a paleotransform fault (Chatzaras et al., 2020 and references therein).

The pyroxenites (~ 5-15 cm-thick) generally cut the peridotite foliation at variable angles, but concordant, locally boudinaged, layers also occur. The samples of this study display textures ranging from cumulitic to porphyroclastic or granoblastic-polygonal. They mostly consist of amphibole-bearing websterites (Amp=5-35 vol%; Opx=40-70 vol%; Cpx ~30 vol%), but minor olivine orthopyroxenites (Opx ~95 vol%; ± 5 vol% Ol and/or Cpx) are also present. Accessory phases include high-Ca (An<sub>82-86</sub>) plagioclase, Cr-rich spinel (Cr#=52-73), sulfides and, occasionally, apatite.

Pyroxenes show high Mg# (Mg# Opx=79-85 and ~92; Mg# Cpx=84-88 and ~94 for the websterites and orthopyroxenites, respectively), coupled to low Al<sub>2</sub>O<sub>3</sub> contents. Amphibole is a high Mg# (78-85) edenite. Application of conventional pyroxene thermometry yield equilibration T=930-995 °C, comparable to the enclosing harzburgite (~950 °C). By contrast, T calculated with Ol-Sp geothermometer for the mylonitic harzburgite provide notably lower values (710-740 °C), suggesting slow thermal equilibration for the whole sequence.

Bulk rocks exhibit variable Mg# (82-91) coupled to REE concentrations ranging between 0.1-10 times chondritic values, with the orthopyroxenites showing the lowest absolute contents. The pyroxenites display flat to LREE-depleted (La<sub>N</sub>/Sm<sub>N</sub>=0.28-0.92) patterns, together with weak MREE-HREE fractionation (Gd<sub>N</sub>/Yb<sub>N</sub>=1.73-1.92) and Eu negative anomalies. As a whole, clinopyroxene REE patterns mirror bulk rocks at higher absolute values.

Putative melts in equilibrium with clinopyroxene of the orthopyroxenites yield high Mg# (~80) and strong boninitic affinity. By contrast, the parental melts in equilibrium with the websterites are characterised by remarkably enriched compositions (REE abundances up to 100 x ch.), variable LREE-HREE fractionation (La<sub>N</sub>/Lu<sub>N</sub>=3-19) and flat to fractionated HREE (Gd<sub>N</sub>/Lu<sub>N</sub>=1-2).

Our new results highlight a remarkable heterogeneity of the forearc mantle due to the emplacement of different subduction-related melts during and after the HT shearing deformation of the host peridotite. We propose that the geodynamic setting of the Bogota mantle shear zone needs to be revised in the light of these new results and preliminary <sup>40</sup>Ar/<sup>39</sup>Ar dating of amphibole (~56 Ma) from two websterites of this study (Teyssier, personal communication).

Chatzaras V., Tikoff B., Kruckenberg S.C., Titus S.J., Teyssier C. & Drury M.R. (2020) - Stress variations in space and time within the mantle section of an oceanic transform zone: Evidence for the seismic cycle. *Geology*, 48, 569-573.



## The Lar alkaline igneous complex: genesis and geochemical features of a subduction-related magmatic event in the Sistan belt (SE Iran)

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**Keywords:** Lar Igneous complex, alkaline magmatism, shoshonitic/ultrapotassic, Sistan Suture Zone.

We present a detailed geochemical and petrographic study on samples from the Lar alkaline igneous complex, which is located in the Sistan belt (SE, Iran), a poorly studied area of the Alpine-Himalayan orogenic belt. The complex is composed of intrusive and hypabyssal rocks with shoshonitic to ultrapotassic affinity with variable silica saturation degree. The most alkaline rocks include lamprophyres, nepheline-syenites and felsic dykes of phonolitic composition, whereas silica-saturated and over-saturated rocks are represented by syenites/trachytic dykes and monzonites, respectively. Lamprophyres and nepheline-syenites show petrographic textures suggesting subsolidus unmixing processes between nepheline and K-feldspar recalling the occurrence of pseudoleucite and represent the most alkaline potassic rocks of the Oligocene magmatism in the Sistan-Lut collisional belt.

Incompatible trace element patterns show geochemical features compatible with a subduction-related setting (i.e., LILE enrichments and HFSE depletions), with the alkaline potassic and silica-undersaturated rocks characterized by higher LREE/HREE fractionation ( $La_N/Yb_N$  from 12 to 22) with respect to the silica-saturated and -oversaturated rocks ( $La_N/Yb_N$  from 10 to 12).

Preliminary investigation on the mineral chemistry highlights that lamprophyres (mg# 0.70-0.79) are in fact cumulates of olivine (Fo up to 75) and clinopyroxene (mg# up to 0.83), thus attesting the absence of near primary melts in the complex. Ne-syenites (mg# 0.50-0.60) show comparable clinopyroxene compositions (mg# up to 0.82) and equilibrium temperature around 950°C, in agreement with the results of phlogopite-melt geothermometer. The nepheline compositions in the pseudoleucite textures indicate stabilization temperatures under 700°C.

The Sr-Nd-Pb isotopic compositions are rather homogeneous and suggest a possible common mantle source for the Lar igneous rocks and that the crustal contamination/assimilation processes affect only the most differentiated products. A geochemical and isotopic-based modelling suggests that the metasomatic agents, which modified the mantle beneath the study area, are mainly constituted by melts derived from carbonate-rich sediments, whereas melts from carbonate-poor sediments are subordinate. In the general framework of the Alpine-Himalayan orogen, magmas of the Lar igneous complex show interesting geochemical similarities with those of the post-leucititic phase of the Neapolitan district in the Roman Magmatic Province, suggesting analogies in the magma genesis among different sectors of the Tethyan realm.

## **Brittle-ductile deformation in high-pressure continental units and deep episodic tremors and slip events**

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*Keywords:* episodic tremors and slip events; dilational shear veins; blueschist facies conditions; brittle-ductile deformation-

The geological record of deep seismic activity in subduction zones is generally limited due to common rock overprinting during exhumation and only a few regions allow studying well-preserved exhumed deep structures. The Northern Apennines (Italy) are one such area, granting access to continental units (Tuscan Metamorphic Units) that were subducted to high-pressure conditions, were affected by brittle-ductile deformation while accommodating deep tremor and slip and then exhumed back to surface, with only minor retrogression.

Our approach is based on detailed fieldwork, microstructural and petrological investigations. Field observations reveal a metamorphosed broken formation composed of boudinaged metaconglomerate levels enveloped by metapelite displaying a pervasive mylonitic foliation. Dilational shear veins occur in both lithologies, but are more common and laterally continuous in the metapelite. They are mostly parallel to the foliation and composed of iso-oriented stretched quartz and Mg-carpholite ( $X_{Mg} > 0.5$ ) fibres, which are single-grains up to several centimetres long. These fibres define a stretching direction coherent with that observed in the metaconglomerate and metapelite, which is marked by K-white mica and quartz. Thermodynamic modeling constrains the formation of the high-pressure veins and the mylonitic foliation to  $\sim 1$  GPa and  $350^\circ\text{C}$ , corresponding to c. 30-40 km depth in the subduction channel.

Dilational shear veins developed in subducted (meta)sediments are a key indicator of episodic tremors and slip events (e.g. <sup>1</sup>). We propose that these structures reflect the repeated alternation of localised brittle failure, with dilational shear veins development, and more diffuse viscous deformation. These cycles were probably related to the fluctuation of pore pressure that repeatedly reached lithostatic values. Concluding, these structures can be considered the geological record of episodic tremors and slip events occurring at  $>30$  km of depth in the Apenninic subduction channel.

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Fagereng Å., Remitti F. & Sibson R.H. (2011) - Incrementally developed slickenfibers - Geological record of repeating low stress-drop seismic events? *Tectonophysics* 510, 381–386.

## Granoblastic dikes in the lower oceanic crust exposed at Atlantis Bank (Southwest Indian Ridge)

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**Keywords:** IODP Expedition 360, amphibole, mineral chemistry, dike emplacement, equilibrium temperature.

International Ocean Discovery Program (IODP) Expedition 360 drilled 809 m-deep Hole U1473A into Atlantis Bank Oceanic Core Complex (57°E, Southwest Indian Ridge). A section of lower oceanic crust was recovered, and nine diabase dikes were sampled at different depths.

Two diabase dikes in IODP Hole U1473A display magmatic mineral assemblage (clinopyroxene [Cpx] and plagioclase [Pl]) and textures suggesting late dikes emplacement in a relatively cool host rock. The other seven dikes, sampled between 292 and 469 mbsf, overall display granoblastic textures (named “granoblastic dikes” by the IODP Exp. 360 Scientific Party) and mostly consist of Pl and brown amphibole [Amph]. They also include minor Fe-Ti oxide phases and sulfides; minor proportions of Cpx and Opx locally occur in small discrete pockets. In this study, we investigate textures and mineral chemistry of the granoblastic dikes to comprehend their formation and to unravel the origin of their relatively high water contents, as documented by the amphibole modal amounts (~50 vol%).

Cores of the granoblastic dikes typically display either intergranular textures with preserved prismatic Pl crystals, or fluidal textures defining a magmatic foliation. The dike rims are mainly characterized by granoblastic textures that often grade to foliated textures approaching the dike/host gabbro contact. Felsic material of dioritic to gabbro-noritic composition occurs along most dike/gabbro boundaries. The felsic material generally shows sharp contacts with the host gabbro, whereas the dike/felsic material contact is irregular and characterized by a gradual decrease in crystals grain size and Pl/Amph modal ratio from the felsic material to the dike. The close association between felsic material and dikes suggests that the felsic material genesis is closely related to the granoblastic dikes.

Brown Amph displays low Cl contents (<0.03 wt%) and lack of substantial chemical variability within single dikes. Overall, brown Amph has 57-67 Mg#, 7.4-11.4 wt% Al<sub>2</sub>O<sub>3</sub>, 1.9-3.1 wt% TiO<sub>2</sub> and 1.6-2.8 wt% Na<sub>2</sub>O. Anorthite contents (An) in Pl are higher and K<sub>2</sub>O lower in the deepest dike 42-2b. Also, Pl chemistry vary between dike cores with higher An to dike rims showing relatively lower An (e.g., dike 42-2b: from An<sub>61</sub> and 0.05 wt% K<sub>2</sub>O to An<sub>43</sub> and 0.09 wt% K<sub>2</sub>O). Pl-Amph equilibrium temperatures range between 850 and 880 °C for the deepest analyzed dike and in the interval 750-810 °C for the shallower dikes. The temperature estimates, together with the observed granoblastic textures and mineral assemblage suggest that the granoblastic dikes equilibrated under granulite to upper amphibolite facies conditions. Compared to granoblastic dikes from fast-spreading environments, the U1473A granoblastic dikes contain remarkably higher modes of brown Amph documenting the involvement of water-rich fluids in their formation. The low Cl contents indicate that such fluids were not solely of seawater origin but included a magmatic component.

## Impact of compositional variability of pelagic clay-rich sediments on the mechanical behavior of accretionary prism

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Keywords: pelagic clay, megathrust, accretionary prism.

Geodetic and seismologic data suggest that strain release at subduction plate boundaries can span a wide range of slip rates, from creeping to ‘normal’ earthquakes, passing through intermediate slip rate as for slow slip, episodic tremors and low frequency earthquakes. These slip behaviors can coexist or alternate in time, especially updip and downdip of the so called ‘seismogenetic zone’. In this scenario, although the mechanisms controlling the nature of slip as well as the relationships between rock physical properties, fault zone composition and fault slip behavior remain undiscovered, several Authors (e.g. Aretusini et al., 2021) suggest that in the shallow part of the subduction zone a key role can be played by the frictional properties of the clay and therefore by the clay content.

We propose the study of pelagic clay-rich sediments of Cretaceous age exposed in the Northern Apennines of Italy (i.e., the Argille Varicolori del Cassio -AVV-), which represent the frontal part of the External Ligurian accretionary prism (Vannucchi & Bettelli, 2002). The AVV reached a maximum temperature of 70°-80°C (Thomson et al., 2010) likely during the collisional stage and after the deposition of the Epiligurian succession, up to 2 km thick. They consist of broken formations, displaying a complex deformation pattern, which is characterized by two generations of superimposed mesoscopic folds, faulted layers, boudinage, and pinch-and-swell structures. Mud injections, swirls, limb thinning, and hinge thickening are commonly associated with folding. Pervasive scaly fabric is widely observed (Vannucchi & Bettelli, 2002).

Throughout systematic chemical, mineralogical and micro- to meso-structural analyses we relate the primary sediments composition with the different styles of deformation, from diffuse to localized, which accompanied the evolution of the exhumed External Ligurian accretionary prism. Our results suggest that: (i) the style and partitioning of deformation and the shear localization were strongly influenced by even small compositional changes, (ii) the partition of deformation and shear localization along lithological boundaries were relevant.

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Thomson S.N., Brandon M. T., Reiners P. W., Zattin M., Isaacson P.J. & Balestrieri M.L. (2010) - Thermochronologic evidence for orogen-parallel variability in wedge kinematics during extending convergent orogenesis of the northern Apennines, Italy. *Bulletin of the Geological Society of America*, 122(7-8), 1160-1179. <https://doi.org/10.1130/B26573.1>.

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## Hydrothermal alteration of ultramafic xenoliths from Miocene tuff breccias from Valle Guffari (southern Sicily, Italy): results from laboratory tests

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*Keywords:* Ultramafic xenoliths, hydrothermal alteration, phyllosilicates.

This contribution presents the preliminary results derived from the mineralogical and petrographic study of hydrothermal alteration of deep seated mantle xenoliths. In ultramafic xenoliths, phyllosilicates are major products of hydrothermal alteration of the main mineral phases such as olivine, orthopyroxenes and clinopyroxenes.

Xenolith rich outcrops were found within the Miocene tuff breccias from Valle Guffari. This locality is situated in the Hyblean Plateau (south-eastern corner of Sicily, Italy), which consists of a thick meso-cenozoic carbonate sequence and of Neogene-Quaternary open shelf clastics with interbedded volcanic basic rocks. On the basis of petrographic and compositional features, collected xenolith population may be divided into: a) ultramafic, which consist of spinel facies peridotites and pyroxenites; b) feldspar bearing suite, mostly represented by metabasite rocks and anorthosites (Atzori et alii, 1999; Punturo et alii, 2000; Punturo, 2010). Moreover, Manuella (2011) reports mineralogical investigations on some Hyblean harzburgite xenoliths, which show serpentinization and related secondary minerals (i.e. sulphides, aragonite, saponite). In this contest, the purpose of the present work is to describe the formation of phyllosilicates [Catalano et alii, 2014] obtained from mantle xenoliths from Miocene tuff breccias exposed, in the laboratory, to various hydrothermal conditions: temperature, 200–800 °C; pressure, 0.1–1.4 kbar; duration of treatment, 6–21 days. Xenoliths were characterized in detail before being used as starting material in hydrothermal synthesis. The starting material and run products were characterized by X-ray powder diffraction (XRPD), scanning electron microscopy with an energy-dispersive spectrometer (SEM/EDS) and differential scanning calorimetry (DSC) and thermogravimetry (TG).

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## **Geochemistry and petrology of plagiogranites in the ophiolites from the Pollino Massif (Southern Italy): Origin and tectonic significance**

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*Keywords:* Pollino Massif, Plagiogranites, geochemistry, petrology, Ophiolites.

In the ophiolitic sequences, are widespread low potassium albite-rich granite, trondhjemite, tonalite and granodiorite (e.g. Koepke et al., 2007). Concerning the Tethyan realm, plagiogranites have been recognized as dikes and beds in the ophiolitic rocks of the western Alps, in Corsica, and in the northern Apennines (Castelli et al., 2002; Montanini et al., 2006). Also if the oceanic plagiogranites are volumetrically minor in the ophiolitic sequences, their origin has been largely debated due to importance of these rocks to understand the Earth's continental lithosphere evolution of (Marien et al., 2019). Several authors (Berndt et al., 2005) proposed that the plagiogranites are the products of fractional crystallization of mid-ocean ridge basalt (MORB) magma at low pressures conditions including, for instance, those exposed in the Oman, Cyprus, Serbia and Turkey ophiolitic sequences (Milovanovic et al., 2012; Kocsal et al., 2017; Marien et al., 2019). Others Authors (Koepke et al., 2007) have suggested an origin by partial melting (i.e. anatexis) of cumulate gabbro (Brophy, 2009; Brophy & Pu, 2012). A further model suggests that plagiogranites formed through the interaction of immiscible liquids with mafic solutions (Kiliç, 2009). Geochemical studies (Koepke et al., 2007; Brophy 2009) stated that the distribution of some elements, including SiO<sub>2</sub>, TiO<sub>2</sub>, and REE, can be used in order to distinguish among these different processes. The aim of this research is to characterize for the first time, with a petrological and geochemical study, the plagiogranites from the ophiolitic rocks of the North Calabria Unit of Pollino Massif and to discuss their origin and geodynamic significance. We also compare the geochemical data of these plagiogranites with those of Western Alps (Castelli and Lombardo, 2007) and Northern Apennines (Borsi et al., 1996; Montanini et al., 2006) and with further Mediterranean plagiogranites such as Turkey (Kocsal et al., 2017), Cyprus (Marien et al., 2019), Serbia (Milovanovic et al., 2012) and Oman (Dylek & Furnes, 2009). The results of this work will provide new contributions and constraints about the geodynamic evolution of the Tethyan realm.

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**S4.**  
**Exhumation processes**

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## Exhumation of the HP eclogites from the Acatlán Complex (south Mexico): new insights from retrogressive microstructures

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*Keywords:* Eclogites, retrogressive microstructures, exhumation, Acatlán Complex.

The Acatlan Complex (Puebla state) is the largest outcrop of metamorphic Paleozoic rocks in Mexico. This Complex is built by metaigneous and metasedimentary units, including polydeformed metagabbros, metabasites, metapelites, serpentinites and granitoids, which have registered, at least, three independent orogenic events that occurred between the Ordovician-Silurian and the early Permian. The most pervasive of these events is the Acatecan Orogen of Early Mississippian age that is characterized for having reached metamorphic peak conditions in the eclogite facies, at up to 22 kbar and 760 °C (Hernández-Uribe et al., 2018). The resulting lithologic and structural diversity has been interpreted as evidence for tectonic processes that involved a complete Wilson cycle, as well as accretionary processes and the subduction of Paleozoic global oceans (e.g. Nance et al. 2006; Ortega-Gutiérrez et al., 2018). For this reason, the Acatlán Complex represents a superb natural laboratory for the complete study of deep-seated inhumation processes and those involved in the eventual exhumation of the rocks that occur in orogenic convergent margins.

In this work, we present a preliminary study based on the metamorphic retrogression of eclogitic rocks from the Acatlán Complex. Field and detailed petrographic observations of these eclogites and associated rocks reveal that their retrogression is preserved in different kinds of microstructures, from plagioclase-epidote and amphibole-plagioclase symplectites, to chlorite-epidote coronae on garnet and titanite rims around rutile. These rocks also record retrograde compositional zoning in garnet, tourmaline, epidote, amphibole and phengite, and different generations of clinopyroxene, garnet, epidote, zoisite, amphibole, plagioclase, biotite, chlorite and calcite. Our observations suggest that the retrogression and subsequent exhumation of this eclogitic rocks took place in at least three stages; thus, our data represents the basis for the reconstruction of critical retrograde segments for the P-T trajectories followed by the Acatlán Complex high pressure lithologies.

This approach provides new elements that eventually could help to solve how HP-rocks generated under more than 75 km deep where exhumed and brought back to the surface.

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## **Titanite from metacarbonates: a (unique) petrological and geochronological tool. An example from the Valle Strona di Omega (Ivrea-Verbano Zone, Western Alps, Italy)**

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*Keywords:* Titanite, U–Pb ages, trace elements, metacarbonate.

The Ivrea-Verbano Zone (IVZ) is a well-exposed middle-lower continental crustal section located in the southern Alps of northwest Italy. This crustal section consists mainly of middle-high grade metapelites and metabasites (Kinzigite Formation) with numerous marble lenses. In particular, the Kinzigite Formation is best exposed in the Valle Strona di Omega, showing progressively higher T conditions, from amphibolite to granulite facies, with increasing crustal depth. Several previous studies focused on the P-T conditions of the metapelites and metabasites (e.g., Kunz and White 2019 and references therein).

We present new petrological and geochronological data for metacarbonate rocks occurring at the different crustal levels. We focus on titanite (CaTiSiO<sub>5</sub>), which is a common and almost unique accessory mineral in the metacarbonates for the lack of other petro-chronological tools (e.g. zircon, monazite and rutile). Titanite may contain numerous important geochemical elements, such as REE, Pb, U, Zr and Nb that are useful for petrological and geochronological reconstruction (Kohn, 2017). Major and trace elements were determined for titanite from metacarbonates with different mineral assemblages along the crustal profile. The chemistry of titanite shows interesting correlations with lithologies, mineral assemblages and titanite modal abundance. Zr-in titanite thermometer (Hayden et al 2008) provided temperature estimates ranging from 700 to 900 °C, coherently with the high temperature conditions recorded by surrounding metapelites/metabasites at Carboniferous-Permian interval (Kunz and White, 2019; Redler et al., 2012). The titanite U concentration ranges from about 20 to 300 ppm; U–Pb dating was only performed for titanite grains from granulite facies metacarbonate, containing more than 100 ppm of U. Preliminary U–Pb dates range from Middle Triassic to Lower Jurassic, suggesting a decoupling between Zr-in titanite geothermometer and U–Pb isotopic results.

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## Microstructural and petrological characterization of a major extensional shear zone in the middle crust (Val d'Ossola, Ivrea-Verbano Zone, Western Alps)

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*Keywords:* continental crust, HT metamorphism, shear zone, microstructures, Ivrea-Verbano Zone.

Shear zones localise most of deformation in narrow areas and provide efficient ways to mobilize significant volumes of fluids and melts up and down the crust. Deformation may localise if a specific domain focuses higher differential stress or strain rate with respect the host rocks. This concentration is commonly associated with variations in rock composition/texture, temperature/pressure conditions or presence of fluid/melts, which are even likely the dominant factor for weakening.

In this contribution, we investigate exhumed shear zone developed in the middle crust with the aim to decipher which heterogeneities promoted the strain localisation in a fully ductile regime. We present microstructural and petrological data to characterise the Pressure-Temperature- Deformation (P-T-D) path across a major extensional shear zone of the Ivrea-Verbano Zone (IVZ, Western Alps) exposed along the Ossola Valley, the Anzola shear zone (ASZ). The ASZ developed at the transition between amphibolite and granulite facies conditions and consists of metabasites rock showing mylonitic fabric alternating layers made mainly of clinopyroxene, amphibole and plagioclase porphyroclasts and in recrystallized grains. The SZ boundaries consist in undeformed gabbroic rocks to one side and felsic and mafic granulite to the other side. A calcsilicate layer occurs at the contact among the gabbroic rocks and SZ.

Our preliminary results suggest that deformation in the ASZ took place under granulite/amphibolite facies conditions at approximately between 650-800°C and confining pressures of around 8 kbar. Microstructural and textural data indicate that dissolution-precipitation creep is the dominant deformation mechanism. Evidence of synchronous deformation and mineral reactions of clinopyroxene suggests that metabasite become mechanically weak during the general transformation weakening process. This process was driven by melt flux deformation demonstrated by the occurrence of large amphibole porphyroclasts and interstitial ilmenite. Petrographic and textural observations suggest that the SZ was characterized by melt-rock interaction with the adjacent gabbroic and metamorphic wall rocks. In fact, our results show that the ASZ is extremely heterogeneous consisting by alternation of amphibolitic and calcsilicate layers, supported by the geochemical observations (e.g., occurrence of two different composition cpx: diopside and hedenbergite). The possible pre-existing heterogeneity (i.e., layering and grain-size variations) was probably the loci of concentrated shear deformation (Altenberger, 1997) and the magmatic fluids could be the source of clinopyroxene weakness and of the abundant amphibole. In this last case, geological interpretations already given (Brodie, 1981; Stünitz, 1998) require reappraisal.

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## Local variations of metamorphic record from compositionally heterogeneous rocks: Inferences on exhumation processes of HP rocks from the Adula-Cima Lunga unit

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**Keywords:** HP-HT metamorphism, heterogeneous rock pairings, Fluid-Rock interaction, P-T-t-D path, Adula-Cima Lunga nappe.

The record of metamorphic conditions may be highly heterogeneous in spatially close rocks with different rheology and composition. The Cima di Gagnone area in the Central Alps represents such an example, where 1- to 100 s-meter scale ultrahigh-pressure and high-temperature ultramafic lenses are enveloped within amphibolite-facies metasediments. Structural investigation demonstrate that ultramafics and metapelites experienced a common Alpine deformation history, excluding their coupling within a tectonic mélange (Maino et al., 2021). In this contribution, we present new field observations, microstructural and petrological analyses, and thermodynamic modelling results focused on the metasediments, confirming that these rocks generally experienced medium pressure and medium temperature conditions of 1.0–1.2 GPa and 640–700 °C, followed by a retrograde stage around 0.6–0.8 GPa and 600–675 °C. However, a few samples from the immediate proximity of the ultramafic lenses record significantly higher *P–T* conditions of 1.3–1.7 GPa and 750–850 °C, approaching the high pressure and high temperature conditions of the ultramafic bodies (1.5–3.1 GPa, 650–850 °C). Mineral/bulk chemistry changes during growth of new mineral phases indicate to local melt/fluid interaction (i.e., metasomatism) between metasediments and ultramafics during the high temperature deformation. Preliminary U-Pb LA-ICP-MS dating suggests that zircon grains from the metasomatic reaction zone have been fully re-equilibrated during the early stage of Alpine exhumation (~36 Ma), while the large part of the metasediments records only pre-Alpine ages. Our results documented that, even though metasediments share the same structural evolution with UM, large differences in the local metamorphic conditions ( $\Delta P$  up to 2 GPa;  $\Delta T$  up to 160 °C) are recorded and are not randomly distributed but they are in relation to: 1) deformation (micro)structures, and 2) distance from the UM lenses. Moreover, fluid-assisted metasomatism is furthermore documented as being strongly localized at the interface between ultramafic lenses and the metapelitic host throughout all part of the metamorphic evolution, including the HP-HT stage. Therefore, in the Cima di Gagnone type-locality, the interplay between metapelites and ultramafic exerts a crucial first-order control to allow assemblage equilibrium during HT metamorphism and amphibolite-facies retrogression. Furthermore, the new findings exclude that the different metamorphic record may be attributed only to differential preservation during the retrograde path. We finally discuss these new data into the regional *P–T–t–D* paths and discuss the possible processes that controlled the exhumation of HP rocks.

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## **Chloritoid-staurolite-andalusite-bearing assemblages in the Central Southalpine basement as markers of evolving thermal regime during Variscan convergence and exhumation**

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*Keywords:* Variscan subduction/collision, pre-Alpine andalusite, chloritoid/staurolite-bearing metapelites.

Multi-scale structural analysis and petrologic investigations are carried out to explore the sequence of pre-Alpine chloritoid-, staurolite-, and andalusite-bearing metamorphic assemblages in the poly-deformed crystalline basement of the upper Val Camonica (central Southalpine domain).

The oldest fabric in the Variscan basement of the Upper Val Camonica is the composite S1 foliation. S1 is supported by contrasting mineral assemblages including garnet, chloritoid, and staurolite that developed under intermediate pressure amphibolite facies conditions during the Variscan convergence. S1 is intersected by the dominant late-Variscan greenschist facies foliation S2, which is supported by white mica and chlorite and truncated, in turn, by the base of Permian siliciclastic sequences. The relationship with the sedimentary covers defines a minimum age for the tectono-metamorphic evolution of the pre-Alpine basement.

The special feature of the upper Val Camonica basement in the Southalpine framework is andalusite, which formed in late D1 to early D2 deformation stages. Field relationships and P-T estimates suggest that the Val Camonica andalusite is pre-mid-upper Permian in age and developed during exhumation immediately after the Variscan collision. It follows that the upper Val Camonica andalusite has a different age and tectonic significance with respect to that of other occurrences of pre-Alpine andalusite in the Alps, where andalusite developed during exhumation of Permian – Triassic high-temperature basement rocks.

## New evidence of high-pressure metamorphism in an ophiolite sequence in the Upper Soana valley, Western Alps

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*Keywords:* Western Alps, high-pressure metamorphism, ophiolites.

The Soana valley is located on the border between Piedmont and Aosta Valley regions; it offers countless opportunities for studying the lithological and structural features of the Alpine collisional chain. In particular, the Upper Soana valley displays, from west to east and from lower to higher structural levels, a natural, sectional profile across the Gran Paradiso Massif, the ophiolitic Piedmont Zone, the Santanel nappe and the Sesia-Lanzo Zone. These units represent transposed fragments of the paleo-European continental crust, the Ligurian-Piedmont ocean basin, and the paleo-African continental crust, respectively.

The study area is located at Colle della Borra (2.578 m), within the Piedmont Zone, where new detailed observations on the geological context and on lithologies associated to massive sulphide mineralization, were made. This area pertains to the Colle della Rosa-Dondena Unit (CRD), which has previously been described as a greenschist-facies tectonic unit interposed between two eclogitic-facies ophiolitic units. The ophiolitic sequence exposed at Colle della Borra, consisting of dominant calcschists with subordinate metabasites layers, quartzites and marbles, has therefore been considered to be of Combin type.

In this work, garnet-chloritoid-bearing leaden micaschists, equivalent to those described in previous works (Battiston, 1984) in the adjacent Rosa dei Banchi klippe (Monte Nero eclogitic unit) were found, suggesting the presence of a possible eclogitic-facies metamorphic imprint inside the CRD. The long lasting high-pressure metamorphic history of these micaschists is evidenced by the presence of chloritoid associated either with a main schistosity together with garnet, or with a primary schistosity marked by relict isoclinal folds. The lithological contact between the micaschists and the overlying calcschists is gradational, suggesting its stratigraphic nature.

Furthermore, the finding in calcschists of numerous lawsonite relics completely replaced by epidote, white mica and quartz is clear evidence of the high-pressure metamorphic signature of the Colle della Borra sequence. This suggests that the entire CRD, in which the calcschist is the dominant lithotype, may have experienced, a metamorphic peak at a pressure at least exceeding the greenschist-facies.

The certain presence of previously unreported high-pressure mineral assemblages in the metasediments of the Colle della Borra ophiolitic sequence calls for reconsidering the tectono-metamorphic evolution of the entire CRD and marks the starting point for further studies in this area.

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## Kinematics and geochronology of the Simplon Shear Zone extensional detachment in the Western Alps

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*Keywords:* Simplon Shear Zone, kinematic vorticity, Ar/Ar geochronology.

Together with the South Tibetan Detachment System in the Himalaya and the Brenner Fault in the Eastern Alps, the Simplon Fault Zone (SFZ) in the Western Alps is one of the most studied extensional detachment developed in syn- and post-collisional orogenic settings (Mancktelow, 1985, Cawood & Platt, 2020). The SFZ promoted the exhumation of the western portion of the Lepontine Metamorphic Dome in the Central Alps and it shows an asymmetric structure: the hanging wall shows evidences of brittle deformation, whereas the footwall exhibits ductile deformation resulting in several-hundred meters of mylonites characterized by amphibolite to greenschist facies conditions, from lower to upper structural level (Campani et al., 2010). The hanging wall is divided from the footwall by the Simplon Line (SL), a narrow zone corresponding to a brittle normal fault. The footwall of the SFZ consists of a wide zone (ca. 1-2 km thick) of mylonites referred to as Simplon Shear Zone (SSZ). A lot of shear sense indicators (SCC' fabric, K-feldspar porphyroclasts, quartz grain shape preferred orientation) both at the meso and microscale, point to a top-to-the-SW sense of shear.

In this contribution we present a multidisciplinary study of the SSZ based on kinematic and geochronological data, in order to characterize the whole evolution of the SSZ.

Kinematic analysis through different methods (SC', RGN and oblique grain shape foliation) revealed a clear decrease of the simple shear component in a general shear flow from the lower to the upper structural level, reflecting an increase of pure shear dominated deformation approaching the SL. Syn-kinematic paragenesis, microstructures and quartz c-axis fabrics revealed that shear deformation occurred under decreasing temperature starting from amphibolite-facies up to greenschist-facies. A petrochronological study based on  $^{40}\text{Ar}/^{39}\text{Ar}$  stepwise heating analyses on micas from the studied structural transect of the SSZ allowed to constrain the timing of deformation within the SSZ. Our multidisciplinary approach contributes to better constrain the kinematic and timing of the SSZ.

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## Structural, kinematic, and thermal constraints on shear deformation in the Barbagia Thrust (Nappe Zone, Sardinia, Italy)

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Keywords: mylonites, Variscan basement, kinematic and finite strain, RSCM.

In continental collisions, first-order thrusts accommodate crustal shortening during the nappe stacking and the exhumation of the middle crust (Wex et al., 2017). Although several quantitative methods for structural analysis have been developed over the last 20 years (Xypolias, 2010), few studies in the Sardinian Nappe Zone have dealt with the identification of vorticity gradient in zones of ductile deformation related thrusting. In this sector of the Variscan Belt, a km-scale tectonic contact, the Barbagia Thrust (BT; Montomoli et al., 2018), marks the boundary between the Internal and the External nappes. Meso- and microstructural analysis allow to define four deformation phases. After a D1 contractional deformation, the D2 related to the BT activity was associated with the development of a nearly plurimetric thick high-strain zone and a strain partitioning. The BT displays a top-to-the S-SW sense of shear. All structural elements were refolded by two subsequent deformation phases (D3 and D4). Kinematic vorticity analysis, on BT mylonite, was performed applying the C' shear band (Kurz & Northrup, 2008), the Porphyroclast Aspect Ratio (PAR; Passchier, 1987), and the Rigid Grain Network (RGN; Jessup et al., 2007). The finite strain analysis was carried out by the centre-to-centre method (Fry, 1979). Kinematic and finite strain analyses joined with Raman Spectroscopy on Carbonaceous Material (RSCM; Beyssac et al., 2002) allowed to recognize an increase of the deformation temperature associated with the BT activity. We detected an increase of the component of simple shear towards the high-strain zone from both the hangingwall and footwall rocks, i.e. the Internal and External nappes. Our work highlights the importance to unravel first-order thrusts with the same detail as generally used for ductile shear zone in the hinterland of the belt. Further studies are needed in order to better understand the BT activity during the exhumation of the internal nappes on the external one.

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## Metamorphic P-T conditions characteristic of subduction/collision systems: insights from 2D numerical models

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*Keywords:* numerical model, metamorphic facies, subduction, collision.

Pressure and temperature (P-T) conditions developed in different regions of subduction complexes have been analysed by means of the 2D numerical code SubMar (Marotta et al., 2006) that models the evolution of an oceanic subduction until continental collision. Models characterised by different subduction velocities have been tested to verify: (i) if the velocity of subduction could have an influence on the distribution of P-T conditions characteristic of different metamorphic facies; and (ii) how the distribution of P-T conditions predicted by the models can vary throughout the numerical simulation. Distribution patterns of strain rates and development of different deformation fabrics have also been investigated to analyse under which metamorphic facies conditions they can be developed easier.

P-T conditions predicted by our numerical simulations show that domains characterised by contrasting metamorphic conditions, such as granulite and blueschist metamorphic facies, can be simultaneously recorded in different regions of the subduction complex, in contrast with the widespread idea that different metamorphic series are representative of peculiar geodynamic scenarios. However, the existence of contrasted metamorphic domains widens the interpretation of the paired metamorphic belts proposed by Miyashiro (1973) and could solve the problematic occurrences of contrasting metamorphic imprints that characterise adjacent portions of collisional belts, as the Variscan metamorphic evolutions observed in different areas of the French Massif Central (e.g., Jouffray et al., 2020). In addition, the coexistence of different metamorphic series and thermal gradients in the same geodynamic setting indicates that same tectonic units could have recorded contrasted P-T conditions during their burial and exhumation path, as suggested for rocks belonging to the subduction complex of the Alpine belt (e.g., Roda et al., 2020). Ultimately, we verified that mylonitic fabrics can develop more frequently in metamorphic facies characterised by high P/T ratios, while coronitic fabric can be better preserved in metamorphic facies with low-to-medium P/T ratios.

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## **Twenty million years of supra- to sub-solidus deformation during exhumation of middle crust from the South-European Variscan Belt (Peloritani Mountains, NE Sicily)**

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*Keywords:* trondhjemites, granites, late-Variscan magmatism, shear zones, southern Italy.

Microstructural investigations of late-Variscan trondhjemites (c. 310 Ma) and granites (c. 300 Ma) from the upper-amphibolite facies Aspromonte Unit of the Peloritani Mountains (NE Sicily; Fiannacca et al., 2019, 2020) revealed for the first time shear-zone deformation affecting both granitoids during their cooling, from submagmatic ( $T > 650$  °C) to low temperature solid state conditions ( $T < 450$  °C) (Fazio et al., 2020). The magmatic texture of the granitoids is usually largely preserved, but evidence for non-coaxial shearing is provided by sigmoidal porphyroclasts, mica fish and rare domino-torn boudins in tiny andalusite crystals. The occurrence of widespread chessboard quartz, together with rare submagmatic fractures, points to deformation in the presence of late-Variscan melt, thus constraining the activity of the shear zone during the post-collisional stages of the Variscan orogenic cycle. Submagmatic deformation microstructures were largely overprinted by progressive lower temperature microstructures during cooling of the granitoid bodies. Solid state-high temperature deformation ( $T > 450$  °C) is documented by feldspar bulging, quartz grain boundary migration recrystallization, ribbon quartz and core-and-mantle structures. Finally, low-T subsolidus deformation microstructures consist of quartz bulging, subgrain rotation recrystallization, mica kinks and feldspar deformation twins. No systematic relationship between age or emplacement depth, and deformation mechanisms has been observed by comparing the microstructures developed in the older trondhjemites, emplaced at higher depth (c. 0.5 GPa), and in the younger granites, intruding the trondhjemites after their exhumation at relatively shallow crustal levels (c. 0.3 GPa). The two continuous sequences of submagmatic to low-temperature subsolidus deformation, recorded in both the older and younger granitoids, suggest a duration of c. 20 Ma for shear-zone activity associated to middle crust exhumation in the South-European Variscan Belt.

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## **Rift-related deformation in the lower continental crust: new insights from the multidisciplinary study of the Forno-Rosarolo shear zone (Ivrea-Verbano Zone, Western Alps)**

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*Keywords:* mylonites, rifting process, vorticity, geochronology, thermochronology, Ivrea-Verbano Zone.

The direct observation and investigation of rift-related structures at the mesoscale is not so common. Detailed constraints on the evolution of the main faults and shear zones developed during crustal extension are not always available. The Ivrea-Verbano Zone in the Italian Southern Alps, sample remnants of the former Alpine Tethys rifted margin and provide the opportunity to directly investigate rift-related tectonics. We present the results of a detailed structural and microstructural analysis of the Forno-Rosarolo shear zone (FRSZ, Strona di Omegna Valley; Rutter et al., 2007; Siegesmund et al., 2008), combined with kinematic vorticity analysis, P-T estimates and preliminary data for monazite U-Th-Pb geochronological. The FRSZ is a subvertical high-strain zone oriented NE-SW, it is located in correspondence to the transition zone between the amphibolite and granulite-facies and developed mainly at the expense of paragneiss, felsic granulites, mafic rocks and minor calc-silicates. All kinematic indicators are indicative of a sinistral top-to-the-SW sense of shear.

Vorticity analysis (stable porphyroclasts method and C' shear band method) revealed a non-coaxial flow with a major component of pure shear (between 60% and 65%) acting together with simple shear.

Amphibolite facies condition of deformation (630 °C by garnet-biotite geothermometer and GASP geobarometer. The age of the shear zone is still poorly constrained, its activity is indirectly inferred to be Triassic and rift-related. In order to address this open question, six samples were selected for in-situ monazite U-Th-Pb geochronology. Selected grains have different microstructural position (included in porphyroclasts, along the mylonitic foliation or in matrix) and commonly present complex chemical zoning that can be linked to the tectono-metamorphic history. This new multidisciplinary study allows to better understand the role of the FRSZ in the rifting process also providing useful informations to better describe the opening of the Alpine Tethys.

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## **X-ray quantitative image analyses of progressive symplectite formation during granulite/ amphibolite facies retrogression**

Ortolano G.<sup>1</sup>, D'Agostino A.\*<sup>1</sup>, Fiannacca P.<sup>1</sup>, Rebay G.<sup>2</sup>, Visalli R.<sup>1</sup> & Cirrincione R.<sup>1</sup>

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*Keywords:* image analysis, thermodynamic modelling, Symplectites.

Metamorphic rocks often show evidence of reacting phases, whose chemical reactions have been “frozen” due to rapid rock exhumation rates. Symplectitic textures are an example of such microstructures that depict ongoing reactions events of thermodynamic instability. They generally occur as vermicular intimate intergrowths of two or more reacting minerals. When preserved in exhumed rocks, they can be analysed to extract considerable amounts of petrological information, since they make possible to identify both products and reactants of the metamorphic reaction in progress. In the present work we applied image analysis techniques to unravel the P-T conditions associated with the development of symplectitic microstructures, occurring as Pl-Hbl-Cpx coronitic intergrowths around relict eo-Variscan garnets in a late Variscan amphibolite sample from the Aspromonte Unit (NE Sicily). With the software *Perple\_X* (Connolly, 1990), we calculated PT-pseudosections for the Eo-Variscan prograde evolution and for the subsequent retrograde stage in amphibolite facies conditions. This was opportunely performed using the XRF bulk rock chemistry and the progression of the Effective Bulk Chemistry (EBC – Zuluaga et al., 2005; Ortolano et al., 2014), respectively. In particular the EBC was calculated by means of the software *Quantitative X-Ray Maps Analyser (Q-XRMA)* – Ortolano et al., 2014, 2018), analysing the calibrated X-ray maps of three different micro-domains from the same thin section sample. Such a procedure was functional to isolate the chemical contribution of the reactant phase volumes, that effectively took part in the symplectite-forming reaction. We managed to constrain a) an Eo-Variscan metamorphic peak condition of 12.0-12.6 Kbar and 745-780 °C and b) a retrograde P-T range of 4.8-5.4 Kbar and 540-560 °C, the latter associated with the development of the symplectitic coronae. These results quantitatively constrain for the first time previous petrographic evidences of relatively HP relics preserved within the Aspromonte Unit, depicting also the late-Variscan exhumation stage trajectory.

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**S5.**  
**Adria Plate**

*CONVENERS AND CHAIRPERSONS*

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## Active shortening across the Northern Apennines-Adria fault boundary from continuous offshore GNSS stations

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*Keywords:* off-shore GNSS data, Adria microplate, block modeling, time series analysis.

The position time-series of a GNSS dataset, including 22 continuous stations located on offshore platforms of the Italian ENI company in the northern Adriatic sea, have been analyzed. We use the GAMIT/GLOBK software to process the offshore data together with those from several hundred onshore continuous GNSS stations in the peri-Adriatic region. The obtained displacement time-series of the offshore stations show sometimes clear deviations from linearity, other than peculiar seasonal displacements, conceivably due to the anthropogenic activity. From the displacement time-series analysis, we obtain the ground displacement rates referred to a local tectonically-stable reference frame (Adria-fixed), obtained by minimizing the horizontal velocities of 75 stations in northern Italy, to better characterize the linear trend of the time series and their deviations. A trend-filtering approach has been adopted to analyze each position components independently, for each station, in order to distinguish the seasonal terms from piecewise linear trends. The latter, and the estimated trend change points, have been compared with data from monthly hydrocarbon production. We find for some stations that deviations from linearity in the horizontal components are temporally correlated with changes in the rates of gas volume extractions. Moreover, the linear long-term trends, even without any deviation, can be influenced by the local deformation due to the constant reservoir depletion. To discriminate whether the horizontal linear rates of the offshore GNSS stations are representative of the occurring tectonic deformation or not, we define a criterion based on an interpolation of the tectonic velocity field for the study area. Horizontal velocities of onshore and selected offshore stations allow to provide some new constraints on the kinematics of the active, mainly offshore, outer thrust front of the Northern Apennine chain in the central and northern Adriatic region. We use a kinematic elastic block model defined on the basis of geological and seismological information available for the area, to provide new insights into the fault slip-rates and the spatial heterogeneity of the interseismic coupling of the offshore thrust front. The obtained results provide new hints on the use of offshore, industrial, GNSS stations on resolving interseismic fault coupling, revealing to be fundamental data in order to perform seismic hazard assessments in the central and northern Adriatic region.



## Mechanics of the Raša fault and earthquake hazard on the city of Trieste

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*Keywords:* active faults, macroseismic data, trenching, InSAR, ground motion, Trieste.

On March 26th, 1511 a large historical earthquake occurred in the region of North-Eastern Italy and Western Slovenia. This major event caused heavy damage and reached a maximum macroseismic intensity of IX. Its location, size and causative fault are still under debate. To re-evaluate the 1511 earthquake, we first perform a high-resolution earthquake detection and relocation of instrumental seismicity that allowed us to constrain the geometry of five nearly parallel faults in the region: Ravne, Idrija, Predjama, Selce and Raša faults. All these faults do have an expression in the geomorphology and reach depths of up to 20 km.

Then, we construct InSAR rate maps (over two decades) to measure interseismic strain accumulation with a clear gradient around the Idrija fault but flat elsewhere, implying it as a leading structure in the region with a 2 mm/yr slip rate also constrained by GPS. InSAR also reveals aquifer-derived uplift and subsidence which are bounded by two splays of the Raša fault, indicating a fully locked segment.

We then focus on the Raša fault with an extensive 3D trenching and also combining all the remotely sensed data and field observations where the exposed stratigraphic records uncover the evidence of at least two individual earthquakes. Radiocarbon dating were used to constrain the ages indicating that the most recent earthquake occurred after 1485 A.D.

Finally, we propose to simulate the ground motions expected in Trieste from hypothetical scenarios of Mw 6.0 to 6.9 earthquakes rupturing the Raša and Idrija faults. To simulate the seismic rupture process, we use a method based on a kinematic source model which has the advantage of taking into account the complexity of spatio-temporal rupture history of an extended source. To generate realistic synthetic seismograms, this source model has to be combined with the seismic wave-field propagated in the geological medium. To do so, two different approaches are used: (1) A semi-empirical simulation method based upon the Empirical Green's Function approach. The idea is to simulate the ground motions produced by a large earthquake by summing the recordings of recent small earthquakes that occurred in the region of interest; (2) A purely numerical approach based upon the Spectral Element Method. To properly simulate seismic wave propagation into the geological medium, we design a high-resolution 3D velocity model for the city of Trieste including also effects due to topography. As a validation, the Peak Ground Velocity (PGV) values obtained from simulations are compared with levels predicted by Italian empirical equations. The PGV values are also transcribed into intensity values and compared with the macroseismic intensities of the 1511 historical event.

## Displacement rate measurement in Northeastern Italy by using PS-InSAR and GNSS data

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Keywords: InSAR, tectonics, surface deformation, geodetic data.

Northeastern Italy is an area characterized by an active tectonic regime with a convergence rate of about 2 mm/yr due to the NNW motion of the Adria plate and its counterclockwise rotation with respect to Eurasia. The N-S shortening is accommodated by the Southeastern Alps and the External Dinarides, mainly dominated by active thrust-and-fold systems and strike-slip faults (D'Agostino et al., 2005; Serpelloni et al., 2016).

In the present study, we exploited the potential of geodetic data to extract information about the surface deformation in response to active tectonics.

We used a Multi-Temporal InSAR approach called Stanford Method for Persistent Scatterers (StaMPS). The technique, based on the detection of coherent and temporally stable pixels in a stack of single-master differential interferograms, allows obtaining mean ground velocity maps.

We used Sentinel-1 SAR images acquired in ascending and descending orbits, spanning 2015-2019 temporal interval, as inputs for SNAP2StaMPS and StaMPS software (Foumelis et al., 2018; Hooper et al., 2012). After the PSI processing, we applied spatial-temporal filters and we performed some post-processing operations to obtain reliable PS candidates. We also performed a calibration by using Adria-fixed GNSS velocities to remove orbital ramps and residual atmospheric contributions. Finally, we obtained Line-Of-Sight calibrated mean ground velocity maps for ascending and descending tracks and, after the decomposition, East-West and vertical velocity maps.

According to the results, we identify some deformation patterns, potentially related to active tectonics. Towards the Alps, we notice a positive vertical signal reaching about 2 mm/yr. In contrast, the East-West map shows deformation patterns with 1-2 mm/yr rate on the northeastern sector and on the Friulian pedemountain and plain areas. The analysis and the modeling of these signals will clarify the relationship with active tectonics in the study area.

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## Cross-border challenges in active fault definitions across the Slovenia-Italy border

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Keywords: cross-border faults, active tectonics, seismic hazard.

Slovenia and Italy share a number of cross-border active faults. Cross-border faults include the continuation of the Dinaric fault system into Friuli and the continuation of the Adriatic foreland thrust system into the SE Friuli plain and south Alpine thrusts (e.g., Moulin et al., 2016; Atanackov et al., 2021). Seismotectonic characterization, past earthquake activity, and seismic hazard assessment require a holistic approach, encompassing entire faults and fault systems. Constraining past seismicity and linking historic events with causative faults has proven exceedingly difficult (e.g., Bavec et al., 2013; Patricelli & Poli, 2020; Grützner et al., 2021). This is a challenge across various fields of geology, as faults produce a variety of geological expressions, crossing different settings: marine – Gulf of Trieste, alluvial plain in Friuli, Karst and Slovenian Istria. The need for significantly improved cross-border harmonization has been obvious in most recent efforts, including HIKE, ESHM20, and the new seismic hazard map of Slovenia. We will discuss open questions and challenges in joint characterization of cross-border faults and open an invitation for collaboration in future work.

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## Records of paleoearthquakes in speleothems in the Northwestern Dinarides, Slovenia

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*Keywords:* speleothems, caves, paleoseismic, U/Th dating, speleoseismology, paleoearthquakes.

Speleothems may be used not only as an archive of past climate changes but also as an archive for seismic events if a damage, caused by coseismic deformation is disclosed. While coseismic damage of speleothems has been studied in many places around the world, the method is relatively new in the region of NW Dinarides at the junction with the Southern Alps where caves are ubiquitous. In the present study, damaged speleothems from several caves in the study area are sampled and dated using the U/Th method. We sampled 9 caves distributed along the strike-slip fault system from Rasa to Idrija, where the 1511 Mw7 earthquake took place. In the selected caves, damaged speleothems for which we could rule out collapses due to landslide, flood, ice flow and human activity were sampled and taken for further analysis. The samples were taken from damaged speleothems which in some specific cases show displacement and/or be distinguished by a change in their growth direction. The sample is taken from the post-event part of the speleothem at the contact-surface between the pre and post-event speleothem and therefore provides a good indication of the age of the catastrophic event. As an initial result we retrieve two distinct clusters of dates present in almost all the caves. One of them at 10,000 yr BP and the other one around 3,000 yr BP. The two distinct clusters could be indicative of large earthquakes in the study area. Our results are correlated with newly reported paleoseismic events retrieved from trenching and highlight the importance of speleoseismology in complementing classical paleoseismology. Specifically speleoseismology is important in an area like Northwestern Dinarides characterized by a large number of caves and where trenching is challenging because of the absence of fresh and recent sediments across active fault scarps.

## **Interference between Apennines and Hellenides foreland basins around the Apulian swell (Italy and Greece)**

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*Keywords:* Apulian swell, Taranto trench, Hellenides foredeep, Apulian foreland, Salento offshore, Ionian Sea, interpretation of vintage seismic lines.

The Apennines and Dinarides-Hellenides orogens share the same foreland in Apulia (Southern Italy), and in its submerged southeastern continuation in correspondence of the Salento offshore. In this last setting, the two thrust belt fronts of the opposite and converging orogens become very close (up to 150 km) giving rise, in this area, to one of the largest lithospheric anticlines in the world. Through the interpretation of seismic reflection profiles from CROP and ViDEPI projects, the interference between the Hellenides foreland basin and the southern Apennines one on the Apulian swell have been investigated. The results allow to unravel the tectono-sedimentary evolution of the southern segment of the Adria Plate, subducting both toward W-SW and E-NE and producing the two foredeeps that interfere during Quaternary. The deposits of the Hellenides foreland basin migrated towards W-SW at least from the Oligocene due to the E-NEward flexure of the Adria Plate in the northeastern part of the Ionian sea (i.e., on the area of the future Apulian swell). The same area, arching, was involved in the eastward roll-back of Adria Plate at least from the early Pleistocene, and the sedimentary wedge of the south Apennines foreland basin migrated towards E-NE beginning to occupy by the outermost part of the Hellenides foreland basin. From late Early and Middle Pleistocene the area coinciding with the culmination of the arc, where the two opposite foreland basin were interfering, began to uplift during arching, forming the Apulian swell. Starting from this moment, the Apulian swell became a threshold for sediments coming from the two opposite orogens, and two different narrow depocenters, well separated from each other, represent today the Apennines and Hellenides foredeeps, respectively.

## **New insights into the northeastern edge of Adria plate (Gulf of Trieste) by 3D velocity-depth models from reflection tomography and depth imaging of multichannel seismic data**

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*Keywords:* Adria Plate, External Dinarides, Gulf of Trieste, Multichannel Seismic Data, 3D Velocity-Depth Model.

The NE edge of the Adria plate, over the N Adriatic Sea and the Venetian-Friulian plain, lies at the junction of the Meso-Cenozoic SW-verging External Dinarides and S-verging Southeastern Alps, originated by Adria-Eurasia collision. In the Gulf of Trieste (GT, NE Adriatic), double-polarity foredeep and distal foreland for both the chains, a multichannel seismic reflection dataset acquired by OGS revealed the present-day structural style due to the rheological contrast between the ductile Eocene turbiditic flysch deposits and their rigid NE-ward flexured Mesozoic-Paleogene Friuli-Dinaric Carbonate Platform (FDCP) bedrock. The FDCP aggraded thanks to Mesozoic NE-SW extensional regime, E-ward deflected by the Late Cretaceous-Paleogene External Dinaric orogeny, then filled by the flysch and dissected by the SW-ward verging Karst Thrust, outermost Dinaric ramp that separates the gulf from the Karst Plateau. The Oligo-Miocene Alpine orogeny produced N-ward tilting of the FDCP. The Messinian unconformity, covered by Quaternary sediments, is cut by transpression faults due to the ongoing NNW-ward Adria motion (Busetti et al., 2010; 2013).

We adopted two advanced tomographic techniques, to construct the first well-constrained 3D P-wave velocity-depth model and imaging of flysch and carbonates units and their top surfaces in the eastern GT: 1- traveltimes reflection tomography (Böhm et al., 1999), that allowed resolution of vertical and lateral velocity gradients by a procedure based on ray tracing and simultaneous iterative reconstruction technique (Carrion et al., 1993) and 2- depth seismic imaging, that refined the velocity field through an iterative imaging procedure including pre-stack depth migration, residual move-out analysis and grid tomography (Picotti et al., 2018). The results provide 1450 m as maximum flysch thickness. The top FDCP lies at about 1600 m, 2 km offshore the city of Trieste. This indicates that Karst Thrust is responsible for a vertical displacement of at least 1600-1800 m. This throw is comparable to those of the SW-verging thrusts of the eastern Friulian plain, where geological setting is analogous.

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## From Mesozoic extension to Cenozoic compression in Po Plain and Adriatic Sea

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*Keywords:* Po Plain, Adriatic Sea, Mesozoic extension, Cenozoic compression, Adria plate.

The present-day Po Plain-Adriatic Sea region constitutes parts of the the Adria foreland surrounded by the converging thrust belts of the Southern Alps, the Dinarides, the Albanides and the Apennines. Its complex geological setting is the result of the overlay of two distinct tectono-sedimentary events: a Mesozoic extension with the deposition of carbonate units, and a following Cenozoic compression characterized by the deposition of terrigenous sediments. Thanks to an uncommon amount of drillings and 2D/3D seismic data collected during 60 years of hydrocarbon exploration it is finally possible to reveal a detailed reconstruction of the Mesozoic extension and the Cenozoic compression occurred in the Adria plate.

The maximum basin widening was achieved during the Late Triassic-Early Jurassic syn-rift phases which progressively led to the formation of hundred km-wide basins: the Lombardian, Belluno and Adriatic. In the Po Plain (the westernmost portion of Adria plate), the pre-rift architecture was completely disrupted by a NNE striking half-graben system, developed by the particularly intense syn-rift activity of the Lombardian rift. Syn-rift dissection started during Late Norian and reactivated in the Early Jurassic after a brief late Rhaetian pause. In the Early-Middle Jurassic, the continental lithosphere thinning shifted westward towards the Ligurian-Piedmontese area and continued until the oceanic spreading during Bajocian. Then, the whole region underwent thermal subsidence related to a strong post-rift heat flow decrease. During these stages, more than 5000 m of sediments were accumulated in two main depocenters (Lombardian and Belluno basins) whereas less than 2000 m were deposited in the associated ridges and plateau. Long-lasting carbonate platforms (the Istrian and the isolated Bagnolo platforms, to the east and south of the Trento Plateau, respectively) remained confined in marginal areas. In the North Adriatic Sea area, the tectonic activity results milder with respect to the Po Plain and the onset of a single and wide basin deepening occurred during the Early Jurassic. In the Central and Southern Adriatic Sea, after a very confined Late Triassic phase, the Early Jurassic extensional activity produced a series of basins articulated in several intrabasinal reliefs and bounded by long-ranging carbonate platforms, the Apulian to the west and the Dalmatian to the east.

The foreland flexuring started with a Palaeocene-Eocene inflection of the whole area towards the Dinaric/Albanian chain system. From Oligocene to Late Miocene the Po Plain and the north Adriatic areas recorded the inflection towards the Southalpine chain. During late Messinian and Pliocene the Adriatic foreland was involved in the Apenninic and Dinarico-Albanian compression and the evolution of the area was marked by the deactivation of the western Southalpine sector and the inflection peak towards the Apennine chain.



## Harmonization of geological data in the Adriatic Sea

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*Keywords:* EMODnet Geology, harmonization, Adriatic Sea, database.

The European Marine Observation and Data Network (EMODnet) is a Project aimed at the collection and harmonization in European Seas of existing data, to be represented on digital maps freely available through a dedicated portal ([www.emodnet.eu](http://www.emodnet.eu)), in order to facilitate their exchange and re-use. It is subdivided into thematic Lots concerning Bathymetry, Geology, Biology, Chemistry, Physics, Seabed Habitats and Human activities. Each Lot is carried out by a consortium of Institutions collating data for its thematic portal also by means of machine to machine communication.

The Geology Lot ([www.emodnet-geology.eu](http://www.emodnet-geology.eu)) is realized by a Consortium of European Geological Surveys. Information includes data at multiple scale on seafloor sediments grainsize, sedimentation rates, Quaternary geology, pre-Quaternary geology and stratigraphy, coastal behaviour, geological events, mineral resources, submerged landscapes. Metadata and available information collected during the Project are displayed on the Portal. The spatial data, organized in layers, are represented by the geometric primitives lines, points and polygons and the alphanumeric data are stored in harmonized and comprehensive databases, which can be consulted online through Attribute tables.

Within the Project a subgroup of Geological Surveys of circum-Adriatic countries (Slovenia, Croatia, Montenegro, Albania and Italy) has been established in order to work together and provide already harmonized products to the Project. Elaboration has been carried out concerning pre-Quaternary units, as required by the Project, as well as pre-Pliocene units, considered by common agreement more meaningful in the Adriatic setting. In addition, other features to be represented were taken into account within the task “Geological events and probabilities”, coordinated by the Geological Survey of Italy – ISPRA. They include submarine landslides, earthquakes, volcanic centres, tsunamis, fluid emissions and Quaternary tectonics. However, the best achievement of the Adriatic group was the realization of a map of sediment grainsize at 1:250,000 scale, obtained thanks to the collaboration of CNR-ISMAR as well.

Products elaborated for the entire Adriatic Sea highlight the continuity of geological units, as shown by the map of pre-Quaternary deposits, contribute to understand the geological evolution, as is the case of the map of pre-Pliocene deposits, and to outline sedimentary dynamics, as evidenced by the map of seafloor sediments. Moreover, collation of data across national boundaries allows to analyse in their entirety specific features, such as submarine landslides.

## The Messinian Salinity Crisis in the Adriatic Sea

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*Keywords:* Messinian Salinity Crisis, Adriatic Sea, Evaporites.

During the Messinian Salinity Crisis (MSC), the Adriatic Sea was composed of several depositional domains. At that time, the area represented the foreland of the southern Alps, active since the Cretaceous, of the Dinarides, active since the Eocene, and of the Apennines, active since the Paleogene. The Apennines, in particular, played a primary role during the Messinian Salinity Crisis, probably conditioning the connections between the Adriatic, Ionian, and Proto-Tyrrhenian basins.

In the Adriatic area, large amount of geological and geophysical data were acquired in the frame both of hydrocarbon exploration and research projects. Most of them are available through the ViDEPI project (<https://www.videpi.com/videpi>) and the SNAP portal (<https://www.snap.ogs.trieste.it>). As part of this work, we analyzed the seismic profiles from the Gulf of Trieste to the Strait of Otranto. In a first instance, we mapped the base of the Plio-Quaternary sequence (PQb), represented by a high-amplitude reflector. It constitutes the Messinian erosional surface (MES), especially in the Northern Adriatic Sea (NAS), and/or the top of the Messinian evaporites deposits (MED). In the NAS, the evaporites layer is absent. Nevertheless, the MES affects the Adriatic Carbonate platform, generating incised paleo-valleys, clearly recognizable in the Gulf of Venice and the Kvarner area. Few patches of evaporites would also occur above the Adriatic foreland.

Toward the Central Adriatic Sea (CAS), MED thickness progressively thickens from a few tens to a maximum of 200 meters. The occurrence of several channel systems is a peculiar characteristic of the CAS; they cut the MED and the Mid Adriatic Ridge. MES is present in the central portion of the CAS, while in the Pescara foredeep the Messinian layer becomes more continuous without erosion evidence at the top.

The boundary between the CAS and Southern Adriatic Sea is represented by the Gargano/Tremiti/Palagruza structural highs. Similar to the Apulian carbonate platform, which is highly eroded by the MES, and subsequently covered by a thin Post-Messinian sequence. In the deeper basinal domain, a few meters of MED are present. Thus, is partially eroded, even in the deeper portion of the South Adriatic basin.

We suggest that the high variability of the relatively thin evaporites layer, may be influenced by different factors, including i) non-deposition, ii) subaerial erosion (discontinuous surfaces), iii) subsea erosion (channels). In this work, the different roles of these factors are analyzed, considering the Messinian connection between the Adriatic Sea and the Mediterranean Sea.

## Deriving a new crustal model of Northern Adria: the Northern Adria Crust (NAC) model

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*Keywords:* crustal model, Northern Adria microplate, Moho geometry, geophysical properties.

The northernmost edge of the convergent margin between Eurasia and the Adria microplate is in the area of transition between Eastern Alps and External Dinarides. This area is the most seismically active area of the Alps, and several destructive earthquakes hit this region in historical times. The stress and strain tensor inversions from the focal mechanisms show a complex stress field with a resulting heterogeneous deformation pattern.

Here, we present NAC (Northern Adria Crust): a 3D model of the geophysical crustal properties in this area (Magrin, Rossi, 2020). NAC has been built by critically choosing and integrating all available information about the depth of the main interfaces and the physical properties of the crust. We started from a VP dataset, and we converted it in VS and density by using empirical relations, tuned through the comparison with the available data from local tomographic inversion, and considering the lithologies of the area. Uncertainties and reliability of the model are quantified, taking into account the data quality and the interpolation procedure. NAC has two versions, with a different structure of the Moho: the first version considers one continuous surface for the whole area, while the second one implies three separate surfaces for the Adria microplate, Eurasia, and the Pannonian fragment. The differences between the two models are minimal, but the available data better sustain the solution of the fragmented crust. For its characteristics of multiparametric information and resolution, NAC can be precious for any purpose and use, where a detailed knowledge of the crustal structure of this area is required. Moreover, it is easy to improve NAC, including new data on structures or crustal properties.

In the last years, new information on the crustal structures became available (e.g., Stipčević et al., 2020; Sadeghi-Bagherabadi et al., 2021). We compare NAC to some of them, in order to discuss its strengths, limitations, and possible developments.

Magrin A. & Rossi G. (2020) - Deriving a new crustal model of Northern Adria: the Northern Adria Crust (NAC) model. *Frontiers in Earth Science*, 8, 89.

Sadeghi-Bagherabadi A., Vuan A., Aoudia A., Parolai S. & the AlpArray and AlpArray-Swath-D Working Group (2021) - High-resolution crustal S-wave velocity model and Moho geometry beneath the Southeastern Alps: new insights from the SWATH-D experiment. *Frontiers in Earth Science*, 9, 188.

Stipčević J., Herak M., Molinari I., Dasović I., Tkalčić H. & Gosar A. (2020) - Crustal thickness beneath the Dinarides and surrounding areas from receiver functions. *Tectonics*, 37. <https://doi.org/10.1029/2019TC005872>.

## Modeling of crustal and thermal structures from magnetic field data: the case of Adria Plate

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*Keywords:* multiscale analysis, Spectral analysis, magnetic field, Adriatic region, crystalline basement, Curie isotherm.

The north-eastern portion of the Adriatic Sea is characterized by a wide magnetic anomaly extending up to the coast of Croatia, which also represents the main contribution to the magnetic field in Southern Europe up to satellite altitudes. Despite many geological and geophysical studies, the origin and characteristics of this magnetic anomaly are still poorly known.

In this study, we adopted multiscale and spectral methods to investigate the main magnetic properties of the Adriatic crust using a high-resolution aeromagnetic dataset.

Multiscale methods, such as the Multiridge (Fedi et al., 2009) and CDEXP (Baniamerian, 2016) methods are used to detect the depth to shallow intra-crustal magnetic sources, whereas spectral analysis is used to estimate the depth to the crystalline basement and the bottom of magnetic sources, which is often interpreted as the Curie isothermal surface.

The depth to the top of the crystalline basement shows a variable morphology that ranges from 6 to 8 km northward. The depth increases to about 14 km on the western coast of the central Adriatic Sea and about 12 km beneath its southern region. The depth to the magnetic bottom varies from about 26 km northward to 30 km in the central Adriatic region and to about 27 km southward. It also shows a significant depression of the Curie isotherm beneath the Dinarides, where it reaches a maximum depth of around 34 km.

In order to assess the quality of the results, our inferred models are compared to available seismic-interpreted cross-sections and to the map of the crustal heat flow.

Finally, we used the Curie isotherm model as a Dirichlet boundary condition to build a thermal model of the region.

The depth estimates in combination with previous geological and geophysical data may provide additional constraints to better characterize the crustal geometry of the region.

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Fedi M., Florio G. & Quarta T. (2009) - Multiridge analysis of potential fields: Geometric method and reduced Euler deconvolution. *Geophysics*, 74(4), L53-L65.

## Understanding the European and the Adriatic plates from the top down

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*Keywords:* Adria plate, European plate, AlpArray, lithospheric structure, slab, orogeny.

Mountain building is a paradigm still under debate in the greater Alpine area. Open questions remain regarding subduction polarity (was there a switch in the Alps?), slab attachment and detachment, the nature of low velocity domains and differences in the composition of the European and Adriatic Plates. Recent geophysical imaging and (seismo)tectonics studies are of great help in providing vastly improved resolution images of the subsurface structures in the crust and mantle. In particular, the European AlpArray project with its dense seismological network has provided 4-years of data from the entire greater Alpine area, leading us to examine the subsurface with renewed vigour.

In the first part of our talk, we explore the pros and cons of the different geophysical methods that allow us to discern the lithospheric structure, with particular attention to the greater Alpine region and the Adriatic plate. In a second part, we focus on differences and similarities between models that have been proposed to explain the tectonic and geodynamic framework of the circum-Adriatic area, including the Alps, northern Apennines and Dinarides. We highlight first-order differences in the seismological characteristics of the European and Adriatic plates that govern along-strike variation of the orogenic structure of these mountain belts. Finally, we revisit models that have been proposed in the past and show how the new results change our view of how inherited structures have affected crustal and mantle evolution during mountain building.

## New evidence of recent tectonic activity of the Susans-Tricesimo thrust-system (NE Italy)

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*Keywords:* seismotectonics, morphotectonics, paleoseismology, NE Friuli.

The recent tectonic activity of the Susans Tricesimo Thrust System (STTS) was investigated through a multidisciplinary approach. The study area is located in the northernmost portion of the Friuli eastern prealpine border where the SSE verging front of the Southalpine Chain meets the NW-SE trending strike slip structures of the eastern Friuli-western Slovenia domain (Vrabec & Fodor, 2006; Poli & Zanferrari, 2018). At present, the 2-3 mm/yr accumulating deformation (Serpelloni et al., 2016) is released through the interaction among reverse, transpressive and strike-slip faults. The study area corresponds to the epicentral zone of two of the strongest earthquakes of NE Friuli: the 1511 Mw 6.3 and the 1976-77 (Mw ≤ 6.4) sequence (Rovida et al., 2021). In more recent times, two seismic sequences were registered in western Slovenia in 1998 (Mw 5.6) and 2004 (Mw 5.2). In order to further explore the involvement of the STTS during the strongest seismic events occurred in the area, this work is focused on the recent tectonic activity of the structure. Based on a multidisciplinary approach, the deep 3D-geometry of the STTS was reconstructed by combining ENI seismic lines interpretation and hypocentral distribution analysis. The morphotectonic survey conducted in the study area allowed to detect many surficial anomalies at the hanging-wall of the ST thrust. The collected morphotectonic hints clearly depict a NW-SE elongated zone of surficial deformation, highlighting the recent activity of the Colle Villano-W inner thrust. Lastly, the realization of a paleoseismological trench across the Colle Villano-W thrust revealed that the excavated glacial units of the Canodusso Subsynthem (18.000 - 19.000 yr 14C BP) experienced at last two deformative episodes. Particularly, the occurrence of the latest event in historical times seems likely, and the possible correlation with the 1511 or 1976 events must be considered.

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## Evidence of fault-valve behaviors at the northern edge of the Adria microplate

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Keywords: fault-valve behavior, Adria, fluid diffusion, earthquake.

We evidenced a coherent transient signal at the Adria-Eurasia plate boundary by applying the data-driven empirical mode decomposition (EMD) technique (Huang et al., 1998) to the recordings of four tiltmeter sites of the NE-Italy subsurface tilt and strainmeter network. The transient produced a tilt propagating along the main fractures in the 1984–1990 period. Borrowing from classical seismology techniques, we used the uprise times to locate the transient signal source. The propagation velocity is compatible with a fluid diffusion process that starts from a source located close to the hypocenter of the February 10, 1983, Ucea earthquake, MD = 4.2 at the Italy-Slovenia border. Previous analyses on the seismic velocities time variations and tidal admittance evidenced vp/vs and elastic parameters changes compatible with pore-pressure time changes (Mao et al., 1989). These results add to the previous observations from navigation satellite system (GNSS) stations in 2006–2009, ascribed to a transient fluid diffusion from below the Bovec basin (Slovenia) close to July 12, 2004, Bovec–Krn earthquake, Mw = 5.1 (Rossi et al., 2018). These data strongly suggest that the area is subject through time to fault valve behavior episodes that release fluids trapped at depth to the surrounding region as pore-pressure variations (Sibson, 1992). The convergence between Alpine and External Dinarides structures puts highly permeable dolomitic limestones in contact with low-permeable fine-grained limestones and flysch formations. Therefore, the conditions for overpressure generation can be created in the interseismic period, whereas fault movements can enable fluid diffusion in the surroundings in close relation with seismic events. We also estimate the possible fluid influx needed to maintain overpressure and possible discharge across the faults involved in both episodes (David et al., 1994).

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## Role of the long-lived Schio-Vicenza Fault System at the northern Adria plate margin

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*Keywords:* Schio-Vicenza Fault System, inherited faults, strike-slip faulting, zipper junction, Southern Alps.

We present a review of geological and seismological data on the long-lived Schio-Vicenza Fault System (SVFS) at the northern Adria plate margin and provide its geodynamic and seismotectonic interpretation.

The SVFS is a NW-SE trending, high angle complex structure transverse to the Southern Alps fold-and-thrust belt, and has been the object of geological and structural studies for more than a century and a half. The main segment of the SVFS is the Schio-Vicenza Fault (SVF), which has a significant imprint in the landscape across the Eastern Southern Alps and the Veneto-Friuli foreland. The SVFS is divided into a northern segment, extending across the chain between the town of Schio and the Adige Valley, and a southern one, coinciding with the SVF proper. The SVF borders to the east a foreland structural and morphological high formed by the Lessini and Berici Mts., where the Mesozoic bedrock is exposed, and by the volcanic Euganei Hills, separating it from the Veneto-Friuli foreland, and continuing southeastward up to the Adriatic coastline along the blind Conselve-Pomposa Fault. The segments of the SVFS have been active during several tectonic phases with different styles of faulting at least since the Mesozoic, with a well defined long-term dip-slip component of faulting and, conversely, a horizontal one not well constrained.

The SVFS interrupts the continuity of the Southern Alps thrust fronts in the Veneto sector, suggesting that at least it played a passive role in controlling the geometry of the active thrust belt, and possibly also the current distribution of seismic release. In this context, the SVFS, and specifically its SVF segment, has been interpreted as the sinistral strike-slip boundary of the northeastern Adriatic indenter.

The recent activity of the SVFS is highlighted by the moderate seismicity along the northern segment and few geological observations along the southern one. The review of the historical and instrumental seismicity along with active deformation data, shows that the SVFS does not appear to have generated large earthquakes during the last few hundred years, while the focal mechanisms of moderate seismicity points to a dextral strike-slip activity, driven by a N-S oriented compressional regime. These observations are corroborated by the field analysis of antithetic Riedel structures of the fault cropping out along the northern segment. Conversely, the southern segment shows geological evidence of recent sinistral strike-slip activity.

The geological and seismological apparently conflicting data can be reconciled considering the sinistral strike-slip faulting style of the southern segment as driven by the indentation of the Adriatic plate, while the dextral strike-slip style along the northern segment can be explained as a sinistral opening “zipper” type shear zone junction, where intersecting pairs of simultaneously active faults with different sense of shear merge into a single fault system through a zippered section.

## **S6.**

# **Coupling deep mantle structures with surface processes and magmatism along the Tethyan margin**

*CONVENERS AND CHAIRPERSONS*

*Paolo Ballato (University of Roma - Roma Tre)*

*Paola Molin (University of Roma - Roma Tre)*

*Barbara Orecchio (University of Messina)*

*Pietro Sternai (University of Milano - Bicocca)*

## **Constraints on the Timing of Surface Uplift of the Iranian Plateau (Arabia-Eurasian Collision Zone) from Clumped Isotope Thermometry on Pedogenic Carbonates**

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*Keywords:* Orogenic plateau, clumped isotope paleoaltimetry, pedogenic carbonates, surface uplift.

Orogenic plateaus are extensive, elevated, arid, generally internally drained, morphotectonic provinces of low internal topographic relief. They are located along convergent plate boundaries and have a profound impact on regional and global climate, erosional processes, local- to far-field deformation mechanisms and the long-term distribution of biomes and biodiversity. Although the paramount role of large orogenic plateaus in shaping our planet is widely appreciated, the question of why, where, and how some orogenic systems develop large plateaus remains a first-order problem in our understanding of lithospheric evolution and orogenic processes. Here, we present a clumped isotope paleoaltimetry study to document the elevation history of the Iranian Plateau, with the goal of understanding the rates and mechanisms of plateau rise. This plateau is in the Arabia-Eurasia collision zone, has a mean elevation of ~ 1.8 km, steep margins with mountain peaks higher than 4 km, and experienced surface uplift sometime after the middle Miocene as documented by the occurrence of ca. 17-My-old marine deposits in the plateau interior. Preliminary results from early Miocene to Quaternary pedogenic carbonates on the plateau interior and the adjacent, less elevated, intermontane Tarom basin suggest that surface uplift must have occurred between 12-11 and 8 Ma. The lack of significant crustal shortening and thickening during this time interval and the occurrence of a renewed phase of volcanism by ca. 11 Ma suggests that surface uplift may have been driven by deep-seated processes associated with asthenospheric flow.

## **A look at the deep structure and dynamic of the circum-Mediterranean orogens**

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*Keywords:* AlpArray, mantle structure, central Mediterranean, Vp, Vp/Vs.

Understanding the evolution and dynamics of the circum-Mediterranean orogens pass through the definition of the deep structure of the crust and upper mantle. Seismological data are the most often used to define the thermal and compositional heterogeneities of the earth. For the broad Alpine belt, there are still many open questions on active processes and on the interaction between adjacent segments of orogens that necessitate high resolution images. In this study, we emphasize some controversial aspects and unknown points from existing tomographic and receiver function models that revealed peculiar processes of delamination/subduction in the Alps and Apennines.

We will also focus on data coming from the AlpArray initiative, a huge temporary seismological experiment done in past years, which results are decisive for the definition of the Alps deep structure. In our approach, we investigate Vp and Vp/Vs 3D models that more directly yield to discriminate the origin of mantle anomalies. A very comprehensive dataset of earthquakes recorded by more than 1300 stations during the experiment have been analyzed furnishing precious information. We derive some new aspects of the mantle structure in the central Mediterranean area and discuss some new idea base on the reconnaissance of low velocity and high attenuation portion of the upper mantle.

## Rejuvenation of a tectonically inactive mountain belt: insights from the Anti-Atlas (Morocco)

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*Keywords:* Uplift evolution, Landscape paleo-reconstruction.

Topography and drainage systems are powerful recorders of tectonic activity especially in regions with limited geological data. The Atlas-Meseta system of Morocco experienced a late Cenozoic topographic rejuvenation related to mantle dynamics. This recent, large-scale, mantle-driven uplift is documented by a few geological evidence such as uplifted, late Miocene, shallow-water marine deposits in the Middle Atlas Mountains. Conversely, the Anti-Atlas doesn't have any stratigraphic records that may allow deciphering this uplift history. The presence of a high standing, relict landscape and the transient state of river networks, however, can be used to reconstruct the recent surface evolution of this less understood orogen. Furthermore, the Anti-Atlas belt experienced limited Cenozoic crustal shortening and this offers the possibility to investigate the magnitude, timing and rates of the dynamic contribution. In this study, we combine geomorphic analysis of topography, stream profiles, celerity of knickpoints and linear inverse landscape modelling with available geological evidence, to decipher the spatio-temporal pattern of surface uplift in the Anti-Atlas. Our results highlight the presence of a landscape and a river network in a transient state of adjustment, and document ~ 1000 m and ~ 900 m of surface uplift and topographic paleo-relief since at least the Miocene. Furthermore, our analysis indicates that this late Cenozoic, regional topographic resurgence occurred during the late Miocene and is also influenced by climate oscillation, which play a key role in shaping the new topography. This approach allows to quantitatively constrain the transient state of landscape and hence to unravel the contribution of regional, mantle-driven, surface uplift on mountain building processes.

## Ridge jumps and mantle exhumation in the Tyrrhenian back-arc basin

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*Keywords:* back-arc basin, subduction, ridge jumps, Tyrrhenian Sea.

The morphology of back-arc basins is tightly linked to the dynamics of their associated subduction zone. Back-arc basins often present multiple spreading centres that form one after the other (e.g. Mariana subduction zone), propagate and rotate (e.g., Lau Basin) following trench retreat. In some cases, rift jumps can create continental fragments or microcontinents (e.g., Coral Sea, Central Mediterranean, Scotia Sea). The Tyrrhenian back-arc basin, in particular, is characterized by the presence of multiple sub-basins and a discontinuous production of new oceanic crust. Moreover, geophysical data show that the basin seafloor is partly made of exhumed serpentized mantle and local intrusion of magma bodies. All these features reveal a picture of a back-arc basin that is much more complex than that of seafloor spreading at mid-ocean ridges. Importantly, the processes controlling rift jumps and mantle exhumation are still not fully understood, but they are certainly related to the dynamics of subduction and mantle flow.

In this work, we show how episodic trench retreat shapes the morphology of back-arc basins and can produce rift jumps. We use the finite element code ASPECT to model the rifting of continental lithosphere in 2D with boundary conditions that simulate the asymmetric type of extension caused by the trench retreat. We perform a parametric study in which we systematically vary the duration of different extensional phases, simulating episodes of trench retreat. Our results show that when extension is continuous, continental break-up occurs and a spreading centre similar to a mid-ocean ridge develops. On the other hand, in models with multiple extensional phases, ridge jumps consistently occur and are often associated with mantle exhumation between the old and the new spreading ridge. This is in good agreement with what observed in Tyrrhenian basin. Timing and length of ridge jumps may depend on rheological properties of the lithosphere, but, importantly, we show that the resulting back-arc basin morphology is controlled by the duration of the different stages of extension.

## The uplift of a collisional plateau unraveled by river network analysis: the case of the Eastern Anatolian Plateau

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*Keywords:* Eastern Anatolian Plateau, collisional plateau, tectonic geomorphology, river longitudinal profile, chi-plot, topography quantitative analysis.

Orogens of continental collisional zone may include high-standing plateaus, both internally and externally drained. These morphotectonic features contain deposits and landforms essential to reconstruct their topographic evolution. In particular, when endorheic basins are integrated into external drainage networks, the rivers could retain first order information on the modes of capture as well as on the interplay between climate and tectonic processes. The Eastern Anatolian Plateau (EAP) of the Arabia-Eurasia collision zone, is one of the most representative examples of collisional plateau. It has a mean elevation of ~2000 m, presents three main endorheic basins (Van, Sevan and Urmia lakes), and is mostly drained by two river networks: the Kura-Arax drainage system to the NE and the Euphrates-Tigris to the SW. Seismic data indicate the presence of a thinned or totally removed lithospheric mantle beneath the plateau explaining the high heat flow and the late Cenozoic volcanic activity in the area. Despite the great number of studies on the EAP, its uplift history is still debated. In this study we quantitatively investigated the drainage systems (river longitudinal profiles and chi-plots) and the general topographic features (swath profiles, slope, local relief, filtered topography) of the EAP. The results speak to a topographic configuration characterized by a high-standing, low-relief plateau centered in the area of Lake Van, but strongly disrupted by tectonic structures with the formation of local topographic highs and lows that include endorheic basins. The hydrographic pattern is strongly disorganized and controlled by active tectonic structures. The irregular river longitudinal profiles indicate that they are in a transient state of disequilibrium as a consequence of regional uplift, capture events, or more localized tectonic activity. The presence of an uppermost segment characterized by low channel steepness suggests that the plateau interior has not been reached by the erosive wave produced by the uplift. In the chi-plots of the rivers draining the northern portion of the plateau two distinct segments record an increase in uplift rate. Conversely, the chi-plots of the rivers draining the southern sector and the Van and Urmia lakes show a single pattern that could be associated with a constant uplift. This difference in uplift pattern is partially confirmed by the stratigraphic record documenting the passage from a marine to a continental depositional environment. Indeed, according to the age of the most recent marine sediments exposed on the plateau, the northern portion emerged from the sea level around 40 Ma while the central and southern ones around 18 Ma. Among these latter, their elevation decreases to the south. In conclusion, the EAP is a high-standing plateau where the integration of hydrography is ruled by regional differential uplift and active tectonic structures.



## Characterization of 70 Ma-old minette dykes from the Julian Alps, NE Italy

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**Keywords:** Julian Alps, Rio Colan, lamprophyric dykes, MARID-like source, high-spatial resolution LA-MC-ICP-MS U-Pb apatite dating, Adria plate.

Lamprophyres and lamproites carry important pieces of information regarding the evolution of the Earth's mantle. It is widely accepted that these magmas derive from a depleted peridotitic source recharged in incompatible elements by metasomatic processes that can modify the source to a MARID-like (Mica-Amphibole-Rutile-Ilmenite-Diopside) composition. These volcanics are widespread in the circum-Mediterranean terrains, with the Italian peninsula characterized by both lamprophyric (from ~ 235 to ~ 34 Ma) and lamproitic (from ~ 34 to ~ 1 Ma) magmatism. In order to step forward in our understanding of the evolution of the lithosphere-asthenosphere transition underneath the Italian peninsula, we report the new occurrence of few lamprophyric dykes cropping out in Rio Colan Valley of the Julian Alps, NE Italy.

Rio Colan dykes are darkish and crosscut with an overall NS orientation an Upper Ladinian to Upper Norian carbonatic sequence. Abundant phenocrysts of biotite-phlogopite and clinopyroxenes showing chemical affinities with minettes, and serpentized olivine are hosted in a holocrystalline matrix. Microphenocrysts of orthoclase, chromites and apatites, mostly included in biotites and clinopyroxenes, are also recognized. Collectively, these observations lead to classify the Rio Colan dykes as minettes. The investigated dykes are high in Mg# (0.73 to 0.79), K<sub>2</sub>O (~ 4 wt%) and Cr+Ni (1060 to 1780 µg/g), but low in SiO<sub>2</sub>, and TiO<sub>2</sub> (~ 46 and 1 wt%, respectively). These data, together with Light Rare Earth Elements (LREE) enrichments (La/Sm ~ 14) and flat chondrite-normalized Heavy REE (Dy/Yb<sub>CH</sub> ~ 1) profiles indicate that the source was a depleted peridotite modified by metasomatism. Ba, Th, Ce, La and P enrichments, high Ce/Pb and low Nb/U coupled with a positive Nb anomaly (i.e. La/Nb ~ 1.4) further indicate that this source, prior to melting, evolved into a MARID-like composition. Two dikes were selected for High-spatial resolution LA-MC-ICP-MS U-Pb apatite dating. All grains gave an age of 70±1 Ma, interpreted as the emplacement age of these minettes. This age and the anorogenic affinity of these minettes are consistent with the regional extensional tectonics. At this time, the Julian Alps were the Dinaric flexural foreland basin which was undergoing NS and NW-SE extensional tectonics caused by the advance of the external Dinaric front due to the subduction towards E of the Adria plate. These results are further compared with coeval and similar Italian and Mediterranean volcanics as these magmas could indicate two distinct macro-domains among the mantle (i.e. sub-continental lithospheric mantle) sources. This will eventually add new insights into the geodynamic setting of the Adria plate at the Cretaceous-Paleogene boundary.

## **Flexural rigidity and isostatic residuals across the Zagros Orogen and the Urumieh-Dokhtar magmatic belt from cross-spectral analysis of topography, gravity, and crustal models**

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*Keywords:* vertical movements, flexural isostasy, Zagros, gravity, crustal loading.

The knowledge on complex structural settings, such as the one of a convergent margin, benefits from the identification of variations in flexural rigidity of the lithosphere that determines its response to the tectonic processes. The study area covers the Zagros Orogen and its associated magmatic belt, representing the most active collisional zone in the Iranian plateau. The Zagros mountains started to raise during the Cenozoic, consequently to the NE-ward subduction of the Neo-Tethyan Ocean.

Regional isostasy, provides a first-order explanation for the observed relationship between topography and gravity, the former exerting a load on the lithosphere, the latter including the signal from the crustal roots compensating that load. Plate flexure generalizes the end-member case of local Airy isostasy to a lithosphere with a finite rigidity, providing the fundamental mechanical model - it results in a low-pass transfer function between topography and roots, the shorter wavelengths being supported by internal stresses. Various cross-spectral analysis methods have been devised to assess this relationship and perform inference of elastic properties.

Our analysis relies on a global model of surface topography (Earth2014, Hirt & Rexer, 2015), a global gravity model, combining satellite and terrestrial data (XGM2019, Zingerle et al., 2019), and a recent Moho depth map (Gvirtzman et al., 2016). First, using the Moho model, we performed a residualization of the gravity field. This field is inverted to determine the intra-crustal loads tied to areas affected by magmatism. We then carried out a load-gravity analysis in the spherical harmonics domain, computing the topo-gravity localized cross-covariance (Wieczorek & Simons, 2005) and the resulting admittance and correlation spectra. Under the assumption that all the topo-gravity interplay can be explained by lateral variations of the integrated rigidity, we obtained the spatial distribution of the best-fitting rigidity through a parameter optimization procedure.

The knowledge of flexural rigidity and magmatic intruded mass allows us to estimate the vertical movement of crust before and after the intrusion, induced by the emplaced load. If the timing of magmatism is known, this approach would allow to predict the temporal evolution of topography.

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## **A petrotectonic model for the Cenozoic porphyry/epithermal mineralizations along the Iranian tectono-magmatic belt**

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*Keywords:* Porphyry deposits, magmatism, productive magma, collision, Cenozoic, Iran.

The subduction of Neotethys oceanic crust beneath Iranian plate along the southern margin of Eurasia during Mesozoic to Cenozoic resulted in the formation of diffused and prolonged arc magmatism, associated with numerous porphyry/epithermal system (PES) deposits. The PES deposits began during Eocene and show a climax during Miocene times, diachronously distributed from northwest to southwest along the convergent margin during progress of the collisional tectonics. Their space distribution is heterogeneous and show concentrations in zones characterized by occurrence of long-lived and stationary magmatic activity, which are located along major, inherited structural weak zones. There, amphibole-dominated fractionation within the lower crustal magma chambers provided metal- and water-enriched residues, which are the source of the productive magmas. Productive magmas correlates with young  $TDM_{Nd}$  ages (younger than 0.7 Ga) and  $^{87}Sr/^{86}Sr_{(t)}$  isotopic ratios ranging from 0.704 to 0.706. We propose that the formation of PES deposits is essentially related to a sequence of several processes, among which the most important are: 1) crustal thickening, due both to magma underplating and collisional shortening; 2) continental lithosphere delamination; 3) partial melting of the enriched arc root; 4) magma upwelling facilitated by the presence of crustal weak zones and 4) emplacement of long-lived magma chambers.

## **Landscape evolution and plate boundary processes: the study case of the Central Anatolian Plateau margins**

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*Keywords:* orogenic plateau, plate boundaries, landscape evolution, numerical modeling.

Orogenic plateaus represent the most spectacular consequence of continental collisions in orogenic belts. The mechanisms related to the growth of an orogenic plateau are still debated and can be the result of multiple tectonic phases and changes in collisional dynamics between the involved plates. In the last decades, the study of landscapes and landforms experienced a significant growth providing new advanced numerical models to relate surface deformation, topographic evolution and plate dynamics. In the Mediterranean area, the Central Anatolian Plateau represents a good example of how different mantle and crustal processes can be involved in building a plateau. The study of the topographic features alongside the plateau margins, such as drainage systems and marine terraces, revealed significantly different uplift histories and mechanisms characterizing the northern and the southern margins. While the northern margin of the plateau experienced vertical uplift from 11Ma ca to the present that can be associated with the transpression along the Northern Anatolian Fault, the southern margin records a fast uplift phase during Pleistocene, causing 1500 km of vertical uplift in about 600.000 years, which has been related to the break-off of the subducting African plate. In our work, we present a summary of how the numerical modeling of the evolution of drainage systems and marine terraces provided significant insights on the uplift history and the topographic evolution of the Central Anatolian Plateau margins, and how these results are linked to the geodynamical processes involving the Anatolian plate boundaries.

## Cenozoic subduction in the Central Alps and the intrusion of the Adamello batholith

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*Keywords:* Southern Alps, Eocene magmatism, Adamello batholith, Alpine geology.

The Adamello batholith is the largest Tertiary magmatic complex of the Alps, and it is mainly composed of tonalites, trondhjemites and granodiorites with minor mafic bodies. Adamello was emplaced at the end of the subduction of the Tethys ocean below the Adria continental margin, when the high pressure metamorphism was at the peak in the Lepontine Alps (Brouwer et al., 2005). The Adamello earlier felsic and mafic plutons are the Corno Alto (including Malga Campo and Monte Ospedale diorites) and the southern Re di Castello (with M. Mattoni, M. Frerone and Blumone mafic apophyses; Bianchi et al., 1970; Tiepolo et al., 2011; Schaltegger et al., 2019). All these magmatic bodies were emplaced along a NE-SW paleo-lineament characterized by extensional/transensional conditions (Laubscher, 1985). This is supported, in proximity of the present Giudicarie lineament, by an extensional paleo - lineament bordering tectonic depressions holding late Cretaceous to Eocene flysch deposits between Upper Val di Non and Bergamo area (Bernoulli & Winkler, 1990). Extensional to transensional conditions were typical of the upper Alpine crust including the Austroalpine and Southalpine domains between Late Cretaceous and Early Eocene (Schmid et al., 2004). In this extensional scenario the first magmatic unfoliated bodies of Adamello were passively intruded in the Southalpine sector. Contrariwise, tonalite plutons, characterized by a pervasive magmatic foliation, were emplaced since the Late Eocene – Early Oligocene when the alpine compressive – to – transpressive deformation was active in the Adria middle crust. This new tectonic phase is responsible for the onset of the Insubric/periadriatic dextral lineament, due to the westward-directed push of the Adria plate and the dominant southward/southeastward directed movement of the Alpine thrust pile including the Southalpine and Austroalpine units

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## **New constraints on the Ivrea Geophysical Body at intra-crustal scales: a combination of gravimetry with passive seismology and rock's physical properties**

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*Keywords:* Ivrea Geophysical Body, gravimetry, seismology, crustal structure.

We present a high-resolution investigation of the Ivrea Geophysical Body (IGB) at intra-crustal scales in the Western Alps. The IGB is a sliver of Adriatic lower lithosphere, located at anomalously shallow depths, and presenting positive gravity and fast seismic anomalies. Despite comprehensive information from previous studies, structural questions persist on the IGB and on its structural relation with the Ivrea-Verbano zone (IVZ), which exposes lower-to-middle crustal composition outcrops at the surface. Therefore, we measured 207 new gravity data points, obtaining a coverage of *ca.* 1 point every 4-to-9 km<sup>2</sup> across the IVZ, and we installed 10 broadband seismic stations (IvreaArray) along the linear West-East profile of Val Sesia, operated for 27 months. We compiled a surface rock-density map and used it to define the density-dependent terrain-corrected “Niggli” gravity anomaly to properly model the IGB density structure at depth. We modelled the IGB as a 3D, single density-contrast interface, obtaining 400 kg·m<sup>-3</sup> as optimal density contrast and a 20-km wide protruding structure, as shallow as 1 ± 1 km below sea level. The seismic data was then used to constrain the IGB shape along the 2D Val Sesia cross-section by means of a joint inversion of seismic receiver functions and gravity anomaly data. This has confirmed the marked density contrast and shallow segments reaching 1 to 3 km depth below sea level, and provide agreement with the rock's physical properties ( $\rho$ ,  $v_s$ ) and the geological structures observed at the surface. These results are now published (Scarponi et al., 2020, 2021).

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## **Granitoids and pyrite bodies exploited similar crustal traps in the Gavorrano Intrusive-Hydrothermal Complex (Tuscany)**

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*Keywords:* crustal traps, pyrite deposits, magmatic-hydrothermal complex.

Gavorrano Intrusive-Hydrothermal Complex (GIHC, Tuscany) is an excellent case study to investigate, through 3D reconstruction of the Complex, the origin and emplacement mechanisms for magmas and hydrothermal fluids in the upper crust.

The evolution of the GIHC starts in the early Pliocene with the sequential emplacement of a cordierite-biotite monzogranite and a tourmaline microgranite at the contact between the Paleozoic basement metapelites and the overlying Mesozoic limestone-dolostone evaporitic formations. The monzogranite is highly porphyritic with megacrysts of K-feldspar (up to 8 cm) and phenocrysts of quartz, plagioclase, biotite, and cordierite. The microgranite is characterised by abundant euhedral microliths (10-500 µm) of black tourmaline set in a fine-grained quartz-feldspar matrix. The small size of the Gavorrano intrusion (ca. 3 x 1 x 0.5 km) and its shallow emplacement level (ca. 5 km) resulted in a thin contact aureole (< 100 m) made of phlogopite-olivine marble and biotite-andalusite pelitic hornfels. A thin and discontinuous layer of vesuvianite-garnet exoskarn is observed replacing the marble at the intrusive contact. The shift to actual hydrothermal conditions is testified by a later episode of hydraulic brecciation affecting host rocks and the skarn. The final stage of GIHC evolution is characterized by chloritization-silicification of the wall rocks and formation of ~30 Mt pyrite ore exploited during the XX century. The pyrite shows variable textures, from microcrystalline to coarse decimetric crystals in veins and it is associated with variable amounts of quartz, chlorite, adularia, fluorite, and sulfide/oxide minerals such as pyrrhotite, magnetite, chalcopyrite, marcasite, sphalerite, and galena.

Surface and underground mapping, integrated by mining reports and drill logs, allowed us to reconstruct the attitude and shape of magmatic and hydrothermal bodies. The GIHC has an overall asymmetric geometry. The western side hosts the main ore bodies in correspondence of the maximum thickness of the magmatic bodies (0.8 km), with an overall sub-vertical, west-dipping attitude. The ore bodies mantle the top and the western flank of the igneous intrusion displaying, in vertical section, a sigmoidal shape with a steep west-dipping thick portion connecting upper and lower tails gently dipping to the west. The eastern side hosts sub-horizontal microgranite bodies with multiple steep west-dipping offshoots.

The collected data led to infer the GIHC western side as the feeder zone for both magmas and hydrothermal fluids. Their ascent was stopped at the contact between the Paleozoic basement and the carbonatic covers. The overall geometries of the intrusive units and pyrite bodies suggest that their emplacement occurred while the country rocks were subjected to deformation with a sense of movement top-down-to-the-west. This close spatial and shape relationship between intrusive rocks and hydrothermal bodies suggests a common extensional tectono-magmatic regime capable to produce crustal traps (dilatational structures) for magmas and ore fluids.



## **Evolution of the Tibet-Indochina orogenic system since 60 Ma: from NE India corner indentation to collapse and eastward flow of Tibet crust**

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*Keywords:* Tibet, GPS, paleomagnetism, active deformation, crustal flow

The Cenozoic deformation of SE Asia has been commonly related to the India-Eurasia collision and to the Tibetan Plateau growth. The huge amount of geological data acquired in Tibet highlighted that the central Plateau is undergoing a NW-SE extension, accommodated by a quasi-continuous SE-ward crust drifting toward Indochina, between the Sichuan and the EHS rigid buttresses (Clark & Royden, 2000). Conversely, some authors described the collision as accommodated by the extrusion of several hundreds of km rigid mega-blocks, bounded by strike-slip faults with hundreds of km of lateral offsets (Tapponnier et al., 1982). Paleomagnetism has proven to be a reliable method to evaluate the displacement of the major strike-slip faults and to describe the crust behaviour. Several authors proposed that the Oligo-Miocene E-SE-ward crust extrusion has been accommodated by the rotation of few major semi-rigid crustal blocks (Li et al., 2017), otherwise, others related the scattered paleomagnetic rotation pattern to the presence of 2-5 km wide blocks, which underwent to independent rotation (e.g., Todrani et al., 2020). We synthesized and re-evaluated all paleomagnetic data collected in Tibet-Indochina assessing with modern and homogenous criteria, estimating the magnitude of the vertical-axis rotation with the coeval Eurasia paleopoles. We focused mainly on SE Tibet and northern Indochina, comparing the paleomagnetic rotation pattern with the present-day geodetic observations. The GPS velocity field shows a large-scale CW rotation of  $\sim 4^\circ/\text{Ma}$  around the EHS, whereas the scattered paleomagnetic rotations display a non-consistent pattern. The Jurassic-to-Oligocene paleomagnetic sites W of the EHS display a prevailing of CCW rotations, while on SE the scattered CW rotations agree with the current kinematics. Moreover, it was suggested that the widespread CW paleomagnetic rotations from northern Indochina have been acquired since Oligocene, while the Pliocene-to-Holocene sites display slight-to-null rotations. Accordingly, we concluded that the revised paleomagnetic rotation pattern agrees with a diffused deformation, mainly active between  $\sim 25\text{-}13$  Ma, is at odds with the present-day geodetic large-scale CW rotation and drifting of the Tibetan crust around the EHS.

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## **Slab folding and surface deformation in the Iran mobile belt**

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*Keywords:* Neotethys, tectonic reconstruction, slab folding, mantle transition zone, back-arc extension.

Back-arc regions are usually punctuated by pulses of tectonic deformation, lasting for few tens of millions of years. Yet, the origin of those short-lived deformation episodes is disputed. Based on an extensive dataset which compiling structural, stratigraphic, geochemical, and geochronological data from Iran, we propose a kinematic reconstruction of the Central Neotethys since 100Ma. We show that the back-arc region of the central Neotethys subduction zone was affected by alternating pulses of extension and compression, which are linked to episodes of trench retreat and advance, respectively. To back up these observations and investigate the causes of such a trench behavior, we run 2D numerical models exploring (i) the dynamics of subduction into a viscously stratified mantle, and (ii) the deep slab deformation induced by mineral phase changes at the mantle transition zone. Our results indicate that episodes of trench retreat and trench advance emerge spontaneously by slab folding and penetration into the mantle transition zone. Eventually, the results of our physical model guide our interpretation of the Central Neotethys subduction history. We propose a coupled mantle–surface tectonic evolution model of the Central Neotethys slab that reconciles back-arc deformation and short-lived pulses of upper-plate vertical motion in a unique, dynamically self-consistent model of deep mantle subduction.

## **S7.**

### **Dynamics of the Earth interior**

*CONVENERS AND CHAIRPERSONS*

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*Magdala Tesauro (University of Trieste)*

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## Targeting iron prospective within the Kabul Block (eastern Afghanistan) via hydrothermal alteration mapping using remote sensing techniques

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*Keywords:* remote sensing, Landsat 8, mineral, iron, geology.

The application of remote sensing has significant time- and cost-saving benefits as a technological tool for the delineation of iron prospects. Afghanistan is a prime target for these methods owing to the presence of several metallic and nonmetallic mineral deposits, most of which remain undiscovered. This study aims to target iron prospective areas within the Kabul Block (SE Afghanistan) by detecting hydrothermal alteration zones and iron-bearing minerals, using Landsat 8 OLI/TIRS. With this objective, we applied four different techniques, including false-color composite (FCC), band ratioing (BR), principle component analysis (PCA) via the Crosta technique, and the spectral angle mapper (SAM).

The results of each algorithm are in high correlation with the conventional data. FCC was successful in highlighting the hydrothermal alteration zones, while the BR and PCA techniques were able to detect iron oxide, ferrous and ferric minerals. The SAM algorithm, as expected, detected iron-bearing minerals. The obtained results were validated by previously limited iron occurrences, and favorable/permisible areas are marked by USSR and USGS, presenting high accuracy. Under the findings of this study, 18 iron prospective areas in total were detected throughout the northern, eastern, southern, and central regions of the Kabul Block, including 6 previously verified areas and 12 newly proposed favorable regions.

## **New insights on the dynamics of the Sumatra and Mariana complexes inferred from the comparative analysis of gravity data and model predictions**

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*Keywords:* numerical modelling, gravity anomalies and Earth structure, subduction zone processes.

Subduction is responsible of surface displacements and deep mass redistribution. This rearrangement generates density anomalies in a wide spectrum of wavelengths which, in turn, causes important anomalies in the Earth's gravity field that are visible as lineaments parallel to the arc-trench systems. In these areas, when the traditional analysis of the deformation and stress fields is combined with the analysis of the perturbation of the gravity field and its slow time variation, new information on the background environment controlling the tectonic loading phase can be disclosed.

Here we present the results of a comparative analysis between the geodetically retrieved gravitational anomalies, based on the EIGEN-6C4 model, and those predicted by a 2D thermo-chemical mechanical modeling of the Sumatra and Mariana complexes, representative of the of two types of subduction: ocean–continent and ocean–ocean.

The 2D model accounts for a wide range of parameters, such as the convergence velocity, the shallow dip angle, the different degrees of coupling between the facing plates. The marker in cell technique is used to compositionally differentiate the system. Phase changes in the crust and in the mantle and mantle hydration are also allowed. To be compliant with the geodetic EIGEN-6C4 gravity data and to compare our predictions with the gravity at Sumatra and Mariana, we define a model normal Earth considering the vertical density distribution at the margins of the model domain, where the masses are not perturbed by the subduction process.

Model predictions are in good agreement with data, both in terms of wavelengths and magnitude of the gravity anomalies measured in the surroundings of the Sumatra and Marina subductions. Furthermore, our modeling supports that the differences in the style of the gravity anomaly observed in the two areas are attributable to the different environments – ocean-ocean or ocean-continental subduction – that drive a significantly different dynamic in the wedge area.

## **X-Min Learn: a supervised machine learning approach to perform automatic mineral classification from X-ray maps**

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*Keywords:* machine learning, X-ray maps, AI, Python.

Over the few recent years artificial intelligence has been widely used to help humans in solving complex tasks. Machine learning algorithms have been implemented in many industrial and scientific fields, mainly due to the increasing amount of available data and better computers performances. EDS and WDS X-ray maps allows geodata scientists and petrologists to extract great amounts of semi-quantitative chemical data from rocks' thin sections. X-ray maps, indeed, can be processed by machine learning supervised algorithms as training data to collect valuable pieces of information regarding mineral chemistry. This information can be further handled by artificial intelligence to generate models able to automatically achieve mineral classification from new X-ray maps in few minutes. In this view, we present here some preliminary results obtained through a new experimental pixel-based mineral classification tool (i.e., X-Min Learn) developed in Python. Since a classification task needs to be solved, we implemented a Multi-class Logistic regression algorithm (Alpaydin, 2020) to build models able to recognize several mineral classes from thin sections of rocks. The output of such classifier is based on the maximum probability of each pixel to belong to a certain mineral class. X-Min Learn features a friendly graphical interface that allows users to easily visualize X-ray maps and apply machine learning models to output a classified mineral map. To assess the results of the models, a probability map is also generated to monitor the algorithm classification behaviour. The tool also includes the possibility to build new custom models in a simplified way, also generating various graphics (i.e., loss curves and confusion matrices) useful to evaluate the model learning behaviour. As an example, we applied both an EDS- and a WDS-based model to classify in turn two metamorphic samples from Peloritani Mountains (NE Sicily) and then we compared the results with those obtained through the software "Quantitative X-Ray Maps Analyzer" (Q-XRMA – Ortolano et al., 2018).

Alpaydin E. (2020) - Introduction to machine learning. MIT press.

Ortolano G., Visalli R., Godard G. & Cirrincione R. (2018) - Quantitative X-ray Map Analyser (Q-XRMA): A new GIS-based statistical approach to Mineral Image Analysis. *Computers & Geosciences*, 115, 56-65.

## **Brittle-ductile damage and segmentation of subducting oceanic plates**

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*Keywords:* subduction, slabs, plate tectonics, lithosphere, rheology.

Subducting oceanic plates experience intense normal faulting during bending that accommodates the transition from horizontal to downward motion at the outer rise at subduction trenches. We investigated the consequences of the plate bending on the mechanical properties of subducting slabs using 2D subduction models in which both brittle and ductile deformation, as well as grain size evolution, are tracked and coupled self-consistently. Numerical results suggest that pervasive brittle-ductile slab damage and segmentation can occur at the outer rise region that strongly affects subsequent evolution of subducting slabs in the mantle. This slab-damage phenomenon explains the subduction dichotomy of strong plates and weak slabs, the development of large-offset normal faults near trenches and the occurrence of segmented seismic velocity anomalies and interfaces imaged within subducted slabs. Furthermore, brittle-viscously damaged slabs show a strong tendency for slab breakoff at elevated mantle temperatures that may have destabilized continued oceanic subduction and plate tectonics in the Precambrian.



## Towards an *ab initio* physically-consistent thermodynamic database for deep mantle phases: the case of $\text{Mg}_2\text{SiO}_4$ ringwoodite

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Keywords: *Ab initio*, DFT, thermodynamics, deep mantle, ringwoodite.

A major shortcoming of current thermodynamic databases for phase equilibrium calculations at deep mantle conditions is the lack of reliable, comprehensive and physically-consistent thermodynamic data of the constituent mineral phases. Some of the most popular thermodynamic databases (e.g. Holland & Powell, 2011) are calibrated over the results of selected HT-HP experiments, which may suffer from uncertainties related to technical problems, pressure scale calibration, metastability issues or the unquenchable nature of some mantle minerals. This may lead in turn to assessed thermodynamic properties for mantle phases which may be internally-consistent but clearly suffer from physical unsoundness, thus hindering a close link between thermodynamic modelling, seismological observations and mantle geodynamics. In that sense, *ab initio* calculations based on quantum-mechanical theory are one of the most reliable methods available to obtain information on thermodynamics, phase relations and seismic properties of mineral phases at deep mantle conditions. The striking feature of the so-called density functional theory (DFT) is that it can accurately predict physico-chemical and thermodynamic properties of crystalline solids in a wide range of P–T conditions, without the need of any experimental data.

We performed *ab initio* B3LYP calculations to determine thermodynamic and seismic properties of ringwoodite (ideal formula  $\text{Mg}_2\text{SiO}_4$ ), which represents the stable polymorph of olivine in the lower part of the Earth's mantle transition zone. Thermodynamic properties of ringwoodite that depend on vibrational frequencies (i.e., heat capacities, thermal expansion, isothermal bulk modulus, entropy, enthalpy, Gibbs free energy) have been computed in the framework of quasi-harmonic approximation by a full phonon dispersion calculation or, alternatively, by a modified Kieffer's model splitting acoustic and optic contributions. Both methods reproduce well the vibrational density of states, allowing an accurate determination of the equation of state parameters and thermodynamic properties as well. The calculated heat capacity in the low- to medium-T range is in excellent agreement with the few calorimetric investigations made so far on this phase (Akaogi et al., 2007). The obtained results are then used to predict relevant phase equilibria of ringwoodite in the Earth's deep mantle and to discuss some implications for mantle seismic discontinuities.

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Holland T.J.B. & Powell R. (2011) - An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *J. Metamorphic Geol.*, 29, 333-383.

## Geodynamic and seismological modelling of the recent dynamics of the Central Mediterranean region

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*Keywords:* Central Mediterranean, numerical modelling, seismic anisotropy, shear wave splitting, subduction zone processes.

The Central Mediterranean region in the Tertiary was characterized by intermittent phases of subduction and collision, the opening of back-arc extensional basins (i.e., Liguro-Provençal, Alboran, and Tyrrhenian basins) and episodes of slab lateral tearing, segmentation and break-off that led to the currently complex geological setting. Although the shallow tectonic evolution of the region has been relatively well constrained by abundant geological data, several uncertainties persist about the mechanisms that generated the present-day surface morphology and deep slab geometry.

In this study, we reproduce the recent large-scale evolution of the Central Mediterranean and the associated strain-induced upper mantle fabrics and seismic anisotropy combining geodynamic and seismological numerical modelling techniques. 3D petrological-thermo-mechanical numerical models have been carried out using the viscoplastic code I3MG (Gerya, 2019), to compute the LPO and the synthetic SKS splitting we use a modified version of D-REX (Kaminski et al., 2004) and the softwares package FSTRACK (Becker, 2006), respectively. The subduction models were designed and calibrated according to paleogeographic-tectonic reconstructions of 30 Ma and seismological observations from the Mediterranean region available in the literature. We test different initial configurations in order to optimize the fit between predicted and observed slabs position and obtain a final model configuration resembling the present-day surface and deeper structures. It is found that the opening of back-arc extensional basins in response to the south-eastward retreat of the Ionian slab is a common feature in all models and slab lateral tearing or break-off occurs when Adria continental margin enters the trench. More importantly, we show that structural heterogeneities within the Adria plate and/or the geometry of its Tyrrhenian passive margin have a profound impact on (i) the development of a slab window below the Central Apennines, (ii) the retreat of the Northern Apenninic trench till the Adriatic Sea, and (iii) the retreat of the Ionian slab till the present-day position. In general, this study highlights the importance of coupling macro-scale geodynamic modelling with micro-scale simulations of strain-induced upper mantle fabrics and seismological synthetics in order to better constrain the tectonic evolution of complex convergent margins such as the Central Mediterranean.

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Gerya T. (2019) - Introduction to numerical geodynamic modelling. Cambridge University Press.

Kaminski E., Ribe N.M. & Browaeys J.T. (2004) - D-rex, a program for calculation of seismic anisotropy due to crystal lattice preferred orientation in the convective upper mantle. *Geophysical Journal International*, 158(2), 744–752.

## **Crust-uppermost mantle structure and buoyancy driven flow model beneath the Tyrrhenian basin undermines regional extension and slab retreat**

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*Keywords:* Tyrrhenian basin, ambient noise tomography, shear-wave velocity structure, lithospheric density structure, buoyancy driven flow model.

The Tyrrhenian basin serves as a natural laboratory for back-arc basin studies in the Mediterranean region. Yet, little is known about the crust-uppermost mantle structure beneath the basin and surrounding margins. The knowledge of the crust-uppermost mantle is of paramount importance in the interpretation of the existing shallow crustal data. Here, we present a high-resolution 3D shear-wave velocity model and Moho topography map for the Tyrrhenian basin and its margins using ambient noise cross-correlations. We apply a self-parameterized Bayesian inversion of Rayleigh-wave group and phase velocity dispersions to estimate the lateral variation of shear velocity and its uncertainty as a function of depth down to 100 km. At crustal depths, our results support an exhumed mantle basement rather than an oceanic basement below the Vavilov basin. We observe a strong contrast between the shear velocity structure beneath the northern Tyrrhenian and that of the southern Tyrrhenian. This change in velocity coincides approximately with the location of the 41° Parallel Line providing the first comprehensive seismological evidence for the presence of this lithospheric feature. Our velocity model also reveals the presence of a broad low-velocity zone between 40 and 80 km depth affecting much of the Tyrrhenian basin's uppermost mantle structure and its extension mimics the paleogeographic reconstruction of the Calabrian arc in time. We interpret the low-velocity structure as the possible source of Mid-Ocean Ridge Basalts-and Ocean Island Basalts-type magmatic rocks found in the southern Tyrrhenian basin. Further, we investigate the contribution of buoyancy forces to the regional dynamics by modelling the lithospheric flow field below the Tyrrhenian basin and margins using as input a derived 3D lithospheric density structure for the study area. Lithospheric deformation, mantle flow, and tectonic stress state in the Tyrrhenian region are influenced by the structure, density, and effective viscosity of the crust and uppermost mantle beneath the basin. In general, the geometry of the crust-uppermost mantle suggests that the present day deformation is controlled by the African-Eurasian convergence therefore undermining the extension and slab retreat as the leading processes. Our models also can explain the heat flux, regional geology and magmatism in the Tyrrhenian basin and surrounding margins.

## Physics-Informed-Neural-Network in Geodynamics

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*Keywords:* geodynamics, Deep-Learning, PINNs.

Numerical simulations of geodynamic problems rely mainly on the used of classical methods like Finite Elements, Finite Differences, Finite Volumes, etc...

These methods applied to real-world problems characterized by high (physical and geometrical) complexity require very powerful computational resources. Moreover geodynamic problems are by nature characterized by high uncertainty in the values of many physical parameters so many-query (or scenario) analysis is of paramount importance in this field. Therefore developing a cost-effective surrogate model is of great practical significance. In this sense a new promising trend is the use of Deep-Learning (DL) for developing such models: DL is able to cope with nonlinearity and high dimensional data. In practical applications the quantity of available data is, very often, insufficient to properly train a Neural-Network (NN). In order to overcome this problem in the last few years the Physics-Informed-Neural-Networks (PINNs) have been introduced (see Raissi et al., 2019): PINNs are neural networks that are trained to solve supervised learning tasks while respecting given law of physics described by PDEs. In this presentation some preliminary results about the use of PINNs in the geodynamic context will be presented.

Raissi M., Perdikaris P. & Karniadakis G. (2019) - Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. *Journal of Computational Physics*, 378, 686-707.

## Propagating triangular rifts of the Tyrrhenian Sea

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*Keywords:* triangular backarc basins, extensional modes, tectono-stratigraphy, Tyrrhenian Sea.

The three-dimensional approach in the analysis of extensional basins is fundamental to investigate their evolution. The analysis of the interplay between fault activity and sedimentary infill permits to reconstruct age and style of deformation for every sedimentary basin. In this way the complete process of continental break-up can be understood. The Tyrrhenian Sea is classically interpreted as a backarc basin formed since Serravallian times at the rear of the Apennine-Maghrebian thrust belt during the collision between Africa and Eurasia plates. However, the Tyrrhenian Sea Present configuration is mainly due to the Pliocene-Quaternary tectonic evolution of several sedimentary sub-basins. The tectono-stratigraphic analysis of these basins documents variable ages and a complex structural style that leads to the opening of several triangular basins. The interpretation of seismic reflection profiles calibrated by well data and outcrops permitted us to define a detailed evolution of the Tyrrhenian Sea during Pliocene-Quaternary times. Along the Southern Tyrrhenian Margin, based on fault pattern and different onset of the basin fill, we recognized three main extensional areas: North of Egadi Islands, Castellammare, and Cefalù-Marsili Basin. An eastward progression of extension, from lower Pliocene to lower Pleistocene, has been documented. During the Pliocene the Central Tyrrhenian Sea was characterized by the opening of the Vavilov basin featuring an eastwards migration in three steps. Lastly in the lower Pleistocene the extension migrated along the Eastern Tyrrhenian Margin along the Gaeta Bay-Campania Margin. The reconstruction of the two main triangular basins (Vavilov and Marsili basins) reveals an apex, or proximal zone, and a distal or bathyal zone. The apex zones in the Latium-Campania margin and Sicilian Margin are characterized by overfilled sedimentary basins which architecture displays rift and supradetachment basins. We document that the rifting of the Vavilov and Marsili triangular basin was synchronous from the apex to distal regions around a couple of Euler poles located, respectively, in Latium and Sicily margins. The comparison between the northern and southern margins of the Tyrrhenian Sea permitted us to reconstruct the mode of extension that characterized the Central Mediterranean region during Pliocene-Pleistocene times. The reconstructed evolution provides an explanation for the different kinematic evolution of the Southern Apennine and Sicilian chain and new constraints on the timing and kinematics of the lower plate.

## The Fe-Si-C system at extreme conditions: a combined mineralogical and petrological approach to the study of deep planetary interiors

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*Keywords:* planetart interiors, mineralogy, petrology.

The Earth is an extremely peculiar planet. Its surface is deeply interconnected with the deep interior through many processes, which contribute to maintaining favorable conditions for life. Additionally, the dynamic nature of the core contributes to the generation of a magnetic field, protecting the atmosphere from the intense solar winds.

Now, the discovery of more than 4300 exoplanets places at the forefront the question about their nature in terms of composition and structure of the interior, their habitability, and their potential analogies with the Earth.

A way to answer these questions is to interpret the mass and radius of the observed exoplanets, also considering the composition of the host star as a proxy for the planet's composition. This implies creating models of planetary interiors, using the physical properties for candidate materials as a reference, and calculate mass and radius in order to compare them with observations. The existence of planets orbiting stars with a different composition from the Sun, thus requires determining the physical properties of exotic candidate materials before modelling the interior composition and structure.

With this contribution we aim to show how an experimental approach combining mineral physics and petrology not only can contribute to a better understanding of our planet, but also to the understanding of the nature and properties of distant objects.

We will present a systematic study at extreme pressure and temperature conditions (i.e. 20-200 GPa and 1500-4000 K) on the Fe-Si-C and Si-C systems using samples with different stoichiometries. Data from X-ray diffraction and chemical analyses on the recovered samples were used to investigate the evolution of the phase diagram with pressure and temperature, determine the physical properties of the stable phases and define the melting relations and properties in the two systems.

The results obtained for the ternary system are significant for the Earth's core and to define potential core crystallization paths in presence of a high light elements content. We will show how the properties of an FeSiC alloy with a low carbon and silicon content, can satisfy the existing constraints on core composition only under very specific conditions. Furthermore, assuming an FeSiC alloy with a higher light element content as the main component of a planetary core, four different crystallization paths are individuated, giving rise to way different dynamical behaviors.

The results obtained on the Si-C system, as the thermal equation of state, were used to model different archetypal carbon enriched planets with an Fe core and pure SiC mantle. The evolution of the mass radius plot and dynamic behavior were then compared to the one of the Earth.

## **Geodynamic modelling of lithospheric extension constrained the mechanism for deep crustal earthquakes in the Main Ethiopian Rift**

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*Keywords:* geodynamics, seismicity, Ethiopian Rift, deformation.

The Main Ethiopian Rift (MER), at the northern segment of the East African Rift System (EARS), offers an excellent tectonic setting to study earthquakes and their controlling mechanisms. Here, we use high resolution, 2D-lithospheric scale numerical modeling experiment combined with analysis of seismic moment release using EAGLE dataset to elucidate the mechanism for deep crustal seismicity in the MER. The modeling experiment is calibrated by appropriate rheology and deformation history for the region. Our modeling results clearly indicate the migration of deformation from the Miocene border faults to 30 km wide, 60 km long Pliocene to recent rift floor faults (magmatic segments). While the strain rate is localized at/beneath the magmatic segments, the brittle strain is distributed in wider region. We also estimate the variation of the magnitude of deviatoric stress with depth in the rift. The deviatoric stress has peak values of 80 and 160 MPa at about 6 and 18 km depth, respectively, which shows a good correlation with the very high seismic moment release. We conclude that the depth distribution of crustal seismicity in the MER is controlled by the rheology of the crust.



## Rocks' Rheology and Seismic Attenuation: What do we know?

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*Keywords:* Rocks' rheology, seismic attenuation, Burgers model.

Rheological properties of the rocks, depending on various parameters (grain size, composition, hydrous conditions), determine their deformation mode in response to the tectonic stress. At shallow depths, the rocks show a pressure-dependent frictional (brittle) behavior, which turns in a viscous (ductile creep) behavior, as temperature increases (e.g., Jacquey and Cacace 2021). The brittle-ductile transition (BDT) occurs at depths where the shear stress, driving the two deformation modes, are equal for some given strain rate, composition, stress regime, and thermal gradient. Such a transition marks the maximum depth of the intraplate earthquakes and of fluids circulation in porous media.

Seismological datasets account for real media properties, providing wave propagational attributes (e.g., seismic wave velocities and attenuation) that can be exploited to add constraints to the BDT depth. Seismic wave attenuation can be used as a potential attribute for subsurface characterization. Indeed, its inverse, the seismic quality factor ( $Q$ ), depends on the seismic frequency, as well as on temperature, water content, and grain size of the rocks (e.g., Karato & Spetzler, 1990; Jackson & Faul, 2010). Therefore, it is likely that seismic attenuation and the viscous modes of deformations of rocks can be correlated, based on their dependency on the aforementioned conditions, as expressed by an Arrhenius-type equation (Farina et al., 2019).

In this study, we investigate the quantitative relationships between seismic attenuation and viscous rocks' rheology, especially across the domain where rocks transition from a dominant brittle to a more ductile deformation mode. We rely on a Burgers mechanical model to derive shear wave attenuation ( $1/Q_s$ ), for several dry and wet crustal rheology, thermal conditions, and different strain rate values. This allows us to establish geothermal and mechanical conditions at which the BDT occurs and to cross-correlate this transition to computed shear seismic wave attenuation values. In particular, we observe a relatively significant  $Q_s$  reduction for strain rates of  $10^{-13} \text{ s}^{-1}$ , despite the assumed rock's rheology and thermal conditions. These first results confirm our hypothesis that variations in the  $Q_s$  factor can be effectively used to identify the BDT's depths in tectonically active areas. Ongoing and future works will focus on a further validation of the modelling implications by systematic analyses of observations derived from rocks' laboratory experiments.

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## The role of the asthenospheric window and deglaciation on the present-day uplift of the southern Patagonian Andes

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*Keywords:* uplift rates, Patagonian Andes, deglaciation, mantle dynamics.

The southern Patagonian Andes (~46-56°S) are well suited to investigate the tectonic vs. climatic interactions during mountain building. Oceanic subduction underneath the South America continent occurs jointly with the opening of an asthenospheric window and, during the late Cenozoic, the building and melting of the Patagonian Icefields. Although the asthenospheric window caused regional dynamic uplift estimated in the order of the tenths of mm per year during the last 3 Ma, the present-day uplift rates in the orogenic domain subject to glaciation are measured between ~10-40 mm/yr. These uplift rates are to a large extent related to the glacial rebound since the Little Ice Age (~ AD 1630), but the role of rheological mantle and lithospheric weakening due to the asthenospheric window is currently unconstrained. Here we use numerical thermo-mechanical modeling to estimate the uplift induced by deglaciation of an ice sheet accounting for the rheological effects of asthenospheric thermal anomalies. Our results show two main phases of rock uplift: 1) a rapid increase in the uplift rates below the ice sheet when deglaciation starts, and 2) stable positive uplift rates during the deglaciation. For any tested, plausible rheological setting, the maximum uplift rates is <10 mm/yr in the absence of an asthenospheric thermal anomaly, and >30 mm/yr with thermal anomalies higher than 100°C. The higher the asthenospheric thermal anomaly, the higher and wider the uplift rates, which may also involve initially ice-free regions. Uplift rates similar to those observed today require an asthenospheric thermal anomaly of 150-200°C. We conclude that, although the driver of the present-day uplift rates is the deglaciation, the asthenospheric window largely controls its outstanding magnitude.

## Back-arc spreading centers and superfast subductions: the case of the Northern Lau Basin (Pacific Ocean)

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Keywords: back-arc basins, morphological analysis, geodynamics.

Most of the oceanic crust origins along the mid-ocean ridges, the boundaries between two different lithospheric plates move apart. Seafloor spreading can origin also along back-arc basins, where the regional extensional tectonics causes the progressive thinning of the crust, the formation of a basin intruded by magmatic bodies, and a system of segments of spreading (Uyeda, 1979; Hynes and Mott, 1985). Most of back-arc spreading centers are formed by segments of ridges offset by perpendicular shear zones resembling short transform faults (i.e. the Mariana Spreading Center in the Pacific and the East Scotia Ridge in the Southern Atlantic). Here we focus on the Lau back-arc basin (Zellmer and Taylor, 2001), resulting by the subduction of the Pacific under the Australian Plate. We analysed the morphology of two segments of back-arc spreading ridges and a rift located in different points along the Northern part of the Lau basin. The Futuna Spreading Center (FSC), in the Western region, is located ~790 km from the Tonga trench. It is NE-SW oriented, characterized by a rise 80-km long and 25-km wide. The region shows an alternation of NE-SW elongated ridges and valleys distributed for ~ 50 km east and west from the central rise; the magmatic activity is very intense and characterized by hundreds of volcanoes. At the same latitude, ~580 km from the Tonga trench, there is the NorthWest Lau Spreading Center (NWLSC), a ridge NNE-SSW oriented, 100 km-long and 8 km-wide. Based on magnetic data, we calculated a full spreading rate of 6,2 cm/a. In the eastern part of the basin, at ~230 km from the Tonga trench, is located the Fonualei Rift and Spreading Center (FRSC). The area is characterized by several N-S oriented escarpments and volcanic ridges with fissure eruptions. We performed plate kinematic reconstructions relative to the fixed Australia of the Northern Lau basin for the last 7 Ma and realized 2D numerical models including visco-plastic rheologies and prescribed surface velocities, in an upper plate-fixed reference frame, using the open-source geodynamic code ASPECT (Advanced Solver for Problems in Earth's ConvecTion; Kronbichler et al., 2012). Our models evidence an area of active deformation from the Tonga Superfast Subduction trench to ~800 km westward within the mantle, that matches with the formation of the FRSC and could be responsible for the magmatic production along the FSC and the NWLSC at the same time.

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## Polybaric crystallisation and equilibrium conditions of Mount Amiata volcanic rocks, and their significance in the frame of magma evolution: insight from igneous mineral chemistry and microtexture petrography

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**Keywords:** mineral chemistry, petrology, geothermobarometry, magmatic chamber, Italian magmatism, magma mixing, micro-texture.

Two different levels of magmatic differentiation have been found in the plumbing system of Mount Amiata geothermal field. With the aim to decipher the geometry and structure of the magmatic system feeding the geothermal field, we carried out a micro-textural petrography study, mineral chemistry analysis and thermobarometric cpx-liquid calculation (Masotta et al., 2013) of the Pleistocene lavas, domes and enclaves.

The Pleistocene Mount Amiata volcano is part of the Radicofani – Mount Amiata volcanic system (Conticelli et al., 2011, 2015). The presence of rounded magmatic enclaves testifies the occurrence of a process in which the fresh mafic hot magma was injected into a cooler and mushy crystallised differentiated one, mixing and mingling with the latter (Ferrari et al., 1996; Conticelli et al., 2015; Marroni et al., 2015). The first arrival of mafic magma within the differentiated magma reservoir triggered the chemical mixing with the viscous and extremely differentiated trachydacitic resident magma to form magma batches with intermediate compositions. A reverse differentiation pathway is observed with time of magma emplacement, which is accompanied by decrease of silica contents and increase of MgO and compatible elements passing from early trachydacites to potassic trachybasalt (absarokite) (Conticelli et al., 2015).

Our results support a scenario characterised by an initially intrusion of mafic silica-saturated potassic to calc-alkaline magmas that cumulated at depth and differentiated through crystal fractionation and minor crustal contamination. The magmatic system evolved from basaltic andesite to trachydacite, started from an intrusive event reconciled with the composition of the Radicofani calc-alkaline magma. The changes occurred in the source of magmas brought newly arrival mafic silica-undersaturated magmas which mixing and mingling. In depth basanite undergoes light processes of differentiation testified by the presence of Cr-diopside and fassaite (Huckenholz, 1973; Duda & Schmincke, 1985).

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## The origin of the oldest terrestrial felsic terranes: how geodynamic and petrological forward modelling assists the discovery of the deep past

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*Keywords:* continental crust, 3D geodynamic modelling, petrological modelling, Archean.

Most of the continental crust was produced by the end of the Archean Eon (4.0 – 2.5 Ga). However only a few remnants of the primordial continental crust have survived till present-day (Hawkesworth et al., 2019). As a result, there are still several unresolved issues regarding the processes that assisted its production. The felsic components of the Archean crust are mostly made of Tonalite, Trondhjemite and Granodiorites (TTGs), that are widely regarded as product of partial melting of hydrated basalts (EAT) at high pressure (~1 GPa) and temperature (800

Aiming at describing the first-order processes behind the felsic crust generation and the geodynamic implication of chemical evolution of the coupled system mantle- crust, we conjugate the state-of-the-art of thermodynamic modelling with thermo-mechanical modelling. We employ both 2D and 3D numerical simulation using LaMEM (Kaus et al., 2016; Piccolo et al., 2020) with density and melt fraction taken from petrological phase diagrams representing different stage of chemical refinement of both mantle and hydrated basalts. We explore the effects of mantle potential temperature, radiogenic heat production and the effects of incoming plume on the generation of the primordial continental terranes and we study how the chemical refinement of both mantle and crust assist the generation of plate-like boundaries and how the condition of felsic melts production changes as a function of the mantle potential temperature. Our work highlights the importance of a closer collaboration between petrology and geodynamic community, as it is required to understand how the evolution of chemical composition influence on the lithospheric to mantle scales the behavior of the planet opening interesting challenges and providing insightful information.

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## **Joint Geophysical-Petrological Modeling on the Ivrea Geophysical Body Beneath Valsesia, Italy: Constraints on the Continental Lower Crust**

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*Keywords:* Crustal sections, Western Alps, Ivrea-Verbano Zone.

One of the few near-complete continental crustal sections exposed on Earth's surface is the Ivrea-Verbano Zone (Western Alps, Italy), which is considered as a petro-geophysical reference of the continental lithosphere. Exposed peridotite slivers embedded in lower crustal rocks at the surface and large density, seismic velocity anomalies of the Ivrea Geophysical Body in the subsurface suggest that mantle-like rocks are located as shallow as a few kilometers depth, but the actual composition of the rocks producing these anomalies is unknown. Here we investigate how the published seismological and new gravimetric data in the location of Valsesia could be reconciled with petrologic data and models of the Ivrea-Verbano Zone. We use the *Perple\_X* software to calculate densities and compressional wave velocities for a range of possible deep crustal rock types. We argue that amphibole gabbros (<18 km depth) and pyroxene hornblendites (>18 km depth) provide the best fit to the joint geophysical and petrologic constraints, whereas residual ultramafic rocks and anhydrous gabbros are inconsistent with the existing data. This indicates that the Ivrea Geophysical Body beneath the Valsesia area in the Ivrea-Verbano Zone preserves the structure of an igneous complex formed during magmatic underplating from the crystallization of hydrous mafic magmas. This would imply melting of a damp mantle source that produced a continental crust of an original thickness of up to ~48 km in the Permian, of which ~30 km are exposed at Earth's surface today.



## Teleseismic Anisotropic P-wave tomography of the Central Mediterranean

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*Keywords:* seismic anisotropy, Mediterranean, P-wave tomography.

The Mediterranean is one of the most complex convergent margins on Earth. Its recent tectonic history was characterized by the coexistence of different compressional and extensional phases associated with episodes of orogenesis, slab rollback, slab tearing and oceanic spreading. Since the late 1990s, numerous seismological studies have been carried out in the region aiming at imagining the isotropic and anisotropic structures of the upper mantle. Among the various imaging techniques, isotropic P-wave travel-time tomography was largely used. However, seismic anisotropy is widespread throughout the Mediterranean area and neglecting its effects could introduce significant artefacts in the inversions that could bias our understanding of the Earth's interior structure and dynamics. Here we discard the isotropic approximation and invert for both P-wave isotropic velocity anomalies and seismic anisotropy by using the method proposed by VanderBeek & Faccenda (2021). We find that the magnitude of the isotropic P-wave velocity anomalies are substantially reduced when inverting for seismic anisotropy. This suggests that lateral variations in temperature and/or composition are smaller than what can be inferred from isotropic tomographies. P-wave fast azimuths orient mostly parallel to the trend of the Balcanic and the Alpine orogens in Eastern and Central Europe, respectively. In the Central Mediterranean the P-wave fast azimuths are sub-parallel to the Oligocene/Miocene-to-present retreating direction of the Ionian trench which led to the opening of the Liguro-Provençal and Tyrrhenian basins and rotation of the Corsica-Sardinia block. In synthesis, the pattern of the P-wave fast azimuths is largely consistent with the S-wave fast azimuths determined from the splitting of SKS waves and from Rayleigh waves. This poses further constraints on the interpretation of the regional geodynamic evolution and on the accuracy of the employed inverse method.

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## Seismic Anisotropy and Its Geodynamic Implications in Iran

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*Keywords:* seismic anisotropy, continental margins, dynamics of lithosphere and mantle, kinematics of crustal and mantle deformation.

We used the results of seismic anisotropy as inferred from shear wave splitting analyses of the core-refracted phases and combined them with the quasi-Love wave observations and geodetic measurements to propose a geodynamical model of the Arabia-Eurasia collision zone. A detailed analysis of the non-null splitting and null splitting measurements obtained from a dense temporary network is utilized to investigate the possibility of lateral and vertical variations in the anisotropic parameters and the hypothesis of a dipping anisotropic layer (Sadeghi-Bagherabadi, 2018a; 2018b). The preferred 2-D geodynamical model of the western part of the collision zone suggests that the belt-parallel orientation of fast axes in the western Zagros originates from a lithospheric transpressional deformation. The plate motion parallel pattern in central Iran and western Alborz coincides with the decrease in the lithospheric thickness. Thus, we believe this trend has its origin in the asthenosphere. A combination of the keel effect of the thickened Zagros lithosphere, the asthenospheric edge-driven convection flow and the lithospheric deformation in the shear zones can cause the NW-SE-oriented splitting pattern reported in some parts of central Iran. The asthenospheric flow beneath the thinner lithosphere to the south of the Bitlis suture in northern Iraq is likely the causative mechanism for our observed plate motion-parallel splittings there. The variation of the convergence obliquity along the Alborz and Zagros inferred from analysis of geodetic data implies that a change in the pattern of lithospheric deformation and the consequent anisotropy is expected. The quasi-Love wave observations also indicate that the fast-axis orientations are highly affected by the lateral variations of the LAB depth in the region.

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## High-Resolution Crustal S-wave Velocity Model, the Crystalline Basement Depth and Moho Geometry Beneath the Southeastern Alps, the Western Part of the External Dinarides, and the Friuli and Venetian Plains

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**Keywords:** ambient noise tomography, Eastern Alps, external Dinarides, Friuli plain, Po plain, Moho, basement, phase velocity.

A dataset of continuous recordings from the temporary and permanent seismic networks in Italy, Austria, Slovenia and Croatia is compiled to compute the high-resolution 3D S-wave velocity model of the Southeastern Alps, the western part of the external Dinarides, and the Friuli and Venetian plains through ambient noise tomography. We computed 4050 vertical component cross-correlations to obtain the empirical Rayleigh wave Green's functions. The dataset is complemented by adopting 1804 high-quality correlograms from Nouibat et al. (2021). We applied the 2D fast-marching surface wave tomography method to the phase velocity dispersion curves in the 2–30 s period band. The tomographic local dispersion curves are inverted for 1D S-wave velocity profiles using the non-perturbational and perturbational inversion methods. We assembled the 1D S-wave velocity profiles into a 3D S-wave velocity model from the surface down to 60 km depth (Sadeghi-Bagherabadi et al., 2021). We found the average depth over the 2.8–3.0 and 4.1–4.3 km/s iso-velocity ranges to be reasonable representations of the crystalline basement and Moho depths, respectively. The basement depth map shows that the shallower crystalline basement beneath the Schio-Vicenza fault highlights the boundary between the deeper Venetian and Friuli plains to the east and the Po-plain to the west. The estimated Moho depth map displays a thickened crust along the boundary between the Friuli plain and the external Dinarides. It also reveals a N-S narrow corridor of crustal thinning to the east of the junction of Giudicarie and Periadriatic lines. A comparison of the shallow crustal velocities and the hypocentral location of the earthquakes in the Southern foothills of the Alps revealed that the seismicity mainly occurs in the S-wave velocity range between 3.1 and 3.6 km/s.

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Sadeghi-Bagherabadi A., Vuan A., Aoudia A., Parolai S. & The AlpArray and AlpArray-Swath-D Working Group (2021) - High-Resolution Crustal S-wave Velocity Model and Moho Geometry Beneath the Southeastern Alps: New Insights From the SWATH-D Experiment. *Front. Earth Sci.*, 9, 641113. <https://doi.org/10.3389/feart.2021.641113>.

## **Crustal structure and discontinuities beneath the Nepal Himalaya using seismic ambient noise and teleseismic P wave coda autocorrelation**

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*Keywords:* Nepal Himalaya, Ambient Noise Tomography, 3-D S-wave velocity model, autocorrelation, discontinuities.

Nepal is seismically active region because of its tectonic setting, and it already have hosted many disastrous earthquakes in the past. For a better understanding of the crustal structure, physics of earthquake as well as their detailed high resolution location and monitoring, and to mitigate the real time seismic hazard, an adequate 3 D regional velocity model is needed, but so far, the 3 D velocity structure in this region is poorly understood. Here, we present a new high resolution 3 D shear wave velocity structure down to 60 km depth beneath the Himalaya Nepal using ambient noise cross correlations. In our study, we applied self parameterized Bayesian inversion of Rayleigh wave local group and phase dispersion to compute the lateral variation of shear wave velocity and its uncertainty as a function of depth. Our results show significant lateral variation in crustal structure and thus, correlate well with the known geological and tectonic features of the study area. Pronounced low velocities observed before the Main Frontal Thrust (MFT) likely corresponds to the sedimentary basin that lies in front of the MFT. The high velocity layer sandwiched between two low velocity layers at 10 15 km depth beneath Nepal and a part of South Tibet may indicate the presence of a shear zone whereas low velocity layer at South Nepal at a depth of 15 25 km and under the High Himalaya at a depth of 25 35 km indicates the presence of aqueous fluids with high pore pressure. Further, the low velocities in the mid crust observed at South Tibet might indicate the presence of partial melt. A pronounced high velocity at 40 60 km depth under the High Himalaya suggests that the rocks in this region might be undergoing metamorphism to partial eclogite.

We also present the application of autocorrelation of teleseismic P coda to recover the shallow and deeper interface in the crust beneath Nepal. The results show deposition of sediments up to 9 km in the South of MFT which gradually decreases northward.

Main Himalayan Thrust (MHT) varying from 10--20 km within Nepal, is flat in the South of MFT and deepening towards the North. We also discover that interface between the Indian upper crust and lower crust at a depth of 30 km, which is flat within Nepal. In addition, the Moho in the South of Main Central Thrust (MCT) is also flat and has a depth of nearly 40 km which deepens upto 60 km towards the North of MCT within Nepal. Our results provide for the first time good constraint both on the seismogenesis and on the earthquake hazard in the Nepal Himalaya.

## A comparative study between X-ray computed microtomography and thin sections observation of mantle xenoliths

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*Keywords:* X-ray computed microtomography, mantle xenoliths, texture, petrology.

Investigating the texture and chemistry of mantle xenoliths allow us to constrain the nature of the upper mantle, the mechanism that generate melts and the evolution of the lithosphere beneath regions where no samples were exposed by tectonic activity. Texture, as well as chemical composition and mineralogical paragenesis, reflects the temperature, pressure, stress conditions, melting and/or contamination events undergone before and during the entrapment in the host magma (Pearson et al., 2003). In particular, the distribution of glass pockets (blebs) and veins inside xenoliths, as well as the texture of silicate, oxide and sulphide phases seem to be important in understanding some aspects of mantle metasomatism (Coltorti et al., 2000; Hughes et al., 2016; Lenaz et al., 2017). Classic 2D thin section observation might overlook some textural and mineralogical features, like oriented distribution of some mineral phases, possible interconnection of glass pockets and veins, distribution and morphological features of accessory minerals like sulphides. Extending the textural analysis of mantle xenolith to three-dimensional scale is therefore a potentially powerful tool in petrography and petrology.

By using a multi-scale 3D textural analysis through X-ray computed microtomography (micro-CT), we characterized three mantle xenoliths from different geodynamic settings (i.e. mobile belt zone, pericraton, oceanic hotspot). We used an approach structured in increasing steps of resolution, starting with conventional X-ray micro-CT imaging (voxel size: 30 mm) and moving on to phase-contrast synchrotron-based X-ray micro-CT to reach a voxel size of 0.9 mm.

We performed several exercises to test the effectiveness of micro-CT imaging on textural characterization of mantle xenoliths, comparing the results with the observation of conventional optical microscopy. One of these exercises involve a model to simulate the random sectioning of several thin sections and estimate the probability of accurate modal classification. Furthermore, 3D models obtained allow us to collect several textural information that were impossible to determine in a 2D classification. For example, we identified: spinel layering in one sample (MG10x), presence of gas vesicles in glass of xenolith Bi4, and silicic glass scattered through sample FN38. Moreover, high-density volumes were detected in nodules MG10x and Bi4, showing no relation with the spinel layering in the first one and a preferential concentration along fractures in the latter one.

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## The traces of magmatic pulses in the crustal density structure of the Western African Rift System

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*Keywords:* Termit basin, crustal column intrusion, magmatism, rifting, Western African Rift System, Chad basin.

The Western African Rift System forms an ensemble of narrow and deep basins, inserted into the context of the much broader oval shaped Chad basin, which though is only a few hundred meters deep, up to 450 m. The system includes the Termit, Tenéré, the Tefidet and the Kafra basins. The rift hosts up to 12 km thick sediments, accumulated starting from the first rift cycle active throughout Cretaceous extending from 145.5 Ma to 99.6 Ma. The second cycle of sedimentation continued with the second rift phase from 65.5 Ma to 23 Ma, and continued during the post-rift phase. Both rift phases produced documented volcanism intercalated in the sediment pile. The sedimentation of the Chad basin is described as that of a sag basin, with deposits starting from the end of the first western rift phase.

Our interest lies in defining to which extent the documented volcanism affected the crustal column of the rift basins, and in particular if the crustal densities have been altered. The presence of increased density in the crustal column has implications on the isostatic equilibrium, and the general comprehension of the amount of magmatic rocks substituting the original or stretched crustal column.

The input data that sustain our modeling are the gravity field, a digital terrain model, and a model of the thickness of the sedimentary cover. Such data are much more easily available than the deep seismic profiling reaching the lower crust, available only rarely. The methodology we use demonstrates that the information on the superficial crustal structure together with the gravity field, allows to define the lower crustal structure and density.

We had found the densification of the lower crust below a Large Igneous Province (Paraná basin, Mariani et al. (2013)), which had been interpreted as underplating, and below the Volcanic province in the Southern Alps (Veneto Volcanic province, Tadiello and Braitenberg (2021)). The timing of the magmatism of the West African rift is presumably tied to two pulses of volcanism documented in the rift, associated with the first post-rift phase from 96 to 88 Ma and the second post-rift phase from 23 Ma up to the Quaternary.

Mariani, P., Braitenberg, C., Ussami, N. (2013) - Explaining the thick crust in Paraná basin, Brazil, with satellite GOCE gravity observations. *Journal of South American Earth Sciences*, 45, 209–223. <https://doi.org/10.1016/j.jsames.2013.03.008>.

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## What does it link the surface to the deep Earth's processes? The tectonic evolution of the Congo basin: an example of intracratonic basin

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*Keywords:* Congo Basin, Intracratonic basins, failed rift, basin analysis, 3D numerical models.

The origin of the intracratonic basins (ICBs) is still highly debated and several hypotheses have put forward to explain their long-lasting subsidence, characterized by prolonged intervals of low rate subsidence alternating with episodic accelerations in subsidence rate (e.g., Hartley & Allen, 1994). The Congo basin (CB) is a natural laboratory for investigating the processes that govern the long-term evolution of the ICBs, due to its long tectonic history, during which a large thickness of sediments deposited (up to about 9 km). Its subsidence initiated very probably as a failed rift in late Mesoproterozoic and evolved during the Neoproterozoic and Phanerozoic under the influence of far-field compressional tectonic events, global climate fluctuation between icehouse and greenhouse conditions and drifting of Central Africa through the South Pole then towards its present-day equatorial position (Delvaux et al., 2021).

We reconstructed the depth of the basement and of main sedimentary layers of the CB, by integrating the interpretations of almost 3000 km of seismic reflection profiles with the analysis of the gravity field. The obtained results show a very heterogeneous basement depth, characterized by a series of topographic highs and lows NW-SE oriented (Delvaux et al., 2021; Maddaloni et al., 2021). We further observed the migration of the sedimentary depocenters from the Proterozoic to Jurassic times and lateral thickness variations of the sedimentary layers. Both types of observations reflect a different behavior of the CB during the stages of its evolution, with a progressive decrease in the influence of the initial rift structure.

The rift phase that gave origin to the CB has been simulated applying multidirectional slow divergent velocities to a cratonic block having a central weak zone, representing the suture area between the cratonic pieces composing the Congo craton. The numerical models, after a time lapse of 200 Myr, show the formation of a central circular subsided area, as effect of the radial extension, induced by the asthenosphere upwelling. The main structures, formed within the depressed topographic area, resemble the present-day basement depth of the CB, supporting the hypothesis that the origin of some ICBs can be due to the effect of multi-extensional stress applied on a cratonic area.

Delvaux D., Maddaloni F., Tesauro M. & Braitenberg C. (2021) - The Congo Basin: Stratigraphy and subsurface structure defined by regional seismic reflection, refraction and well data. *Global and Planetary Change*, 198, 103407.

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Maddaloni F., Braitenberg C., Kaban M., Tesauro M. & Delvaux D., (2021) - The Congo Basin: Subsurface structure interpreted using potential field data and constrained by seismic data. *Global and Planetary Change* (under review).

**S8.**  
**Impact of Renewable and Geo-Energies**

*CONVENERS AND CHAIRPERSONS*

*Letizia Anderlini (INGV)*

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## Identification of sites potentially suitable for hydrogen storage in Italy

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*Keywords:* Pure hydrogen storage, decarbonisation, deep saline aquifers.

Hydrogen is attracting global attention as a pillar of the future European system, for the decarbonisation of transport, power and heating, and of fuel-energy intensive industries, thus playing a significant role as a fuel substitute to limit global warming and greatly contributing to the transformation to a low carbon economy by 2050 (Heinemann et al., 2021 and references therein). Large-scale hydrogen storage can help alleviate the main drawbacks of renewable energy generation such as their intermittency and seasonal and geographical constraints, leading to satisfy the energy demand. Storing pure hydrogen in salt caverns has been practiced since the 1970s in Europe. The EU Hystories “Hydrogen Storage In European Subsurface” project aims to provide subsurface technical feasibility studies for a future with pure hydrogen storage in depleted hydrocarbon fields and saline aquifers, which have never been used for this purpose. Although many aspects will be similar to the storage of natural gas underground and CO<sub>2</sub> geological storage, technical developments are still needed to develop this solution, particularly in terms of bio- and geo-chemical impacts of hydrogen storage on the subsurface and in terms of the quality of hydrogen withdrawn from the reservoir. The EU Hystories project proposes to address the main technical feasibility questions and to assess the techno-economical potential of underground large-scale storage of renewable hydrogen in Europe. The National Institute of Oceanography and Applied Geophysics-OGS is the sole Italian research institution involved in such a project, participating as a Third Party through CO<sub>2</sub>GeoNet, and is mainly devoted to the identification of sites potentially suitable for hydrogen storage in the Italian subsoil both on- and offshore.

Here we present the preliminary results from analysis both regional and local scales. This study provides a characterization of the deep saline aquifers building on work assessing potential for CO<sub>2</sub> geological storage (Donda et al., 2011; Civile et al., 2013; Volpi et al., 2015) enhanced with characteristics relevant to hydrogen storage. A detailed study of an onshore site focused on petrophysical characterization of the potential hydrogen storage reservoir is also reported.

Civile D., Zecchin M, Forlin E., Donda F., Volpi V., Merson B. & Persoglia S. (2013) - CO<sub>2</sub> geological storage in the Italian carbonate succession. *Int. J. Greenh. Gas Con.*, 19, 101-116.

Donda F., Volpi V., Persoglia S. & Parushev D. (2011)- CO<sub>2</sub> storage potential of deep saline aquifers: the case of Italy. *Int. J. Greenh. Gas Con.*, 5, 327-335.

Heinemann N., Alcalde J., Miodic J.M., Hangx S.J., Kallmeyer J., Ostertag-Henning C., Hassanpouryouzband A., Thaysen E.M., Strobel G.J., Schmidt-Hattenberger C., Edlmann K., Wilkinson M., Bentham M., R. Haszeldine S., Carbonell R. & Rudloff A. (2021) - Enabling large-scale hydrogen storage in porous media, the scientific challenges. *Energy & Environmental Science*, 14, 853-864. <https://doi.org/10.1039/d0ee03536j>.

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## Using <sup>222</sup>Radon as tracer for areal and vertical distribution of hydrocarbon contaminations

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*Keywords:* NAPL spills, Radon deficit technique, hydrocarbon residual volumes.

Non-aqueous Phase Liquids (NAPLs), including crude oil and its refined products, produce a long lasting impact on the environment due to unwilling releases. Storage sites of fuel and pump stations are often involved in unwilling NAPL spills in the subsoil and/or groundwater. The non-polar nature of these contaminants confers them a slight solubility in water, causing a reduced efficiency of the most common remediation techniques. These limitations result in long-term remediation activities with high related costs. Unconventional characterization methods like the Radon (<sup>222</sup>Rn)-deficit technique are meant to supplement and optimize the conventional approach by providing dense spatial information in quasi-real time, and at a reasonable cost (De Miguel et al., 2020). Schubert (2015) presented a comprehensive review of the use of <sup>222</sup>Rn as a natural tracer to assess subsurface NAPL contamination. In the present work Radon deficit technique was applied to determine the vertical distribution of Rn in groundwater inside a gasoline contaminated area. Twelve passive accumulators PDMS-AC (polydimethylsiloxane mixed with activated carbon) were inserted at different depth inside fenestrated piezometers and left for two weeks to maximize the Rn accumulation. Then they were measured by high resolution gamma spectrometry. PDMS-AC are characterized by a high permeability to Rn and impermeability to water (Voltaggio & Spadoni, 2013). The obtained results suggest the possible application of Radon deficit to find not only the areal but also the vertical distribution of a NAPL contamination in the saturated level. This datum could offer interesting applications to estimate initial and residual volumes of the contaminant during remediation procedures.

De Miguel E., Barrio-Parra F., Izquierdo-Diaz M., Fernandez J., Garcia-Gonzalez J.E. & Alvarez R. (2020) - Applicability and limitations of the radon-deficit technique for the preliminary assessment of sites contaminated with complex mixtures of organic chemicals: A blind field-test. *Environment International*, 138.

Schubert M. (2015) - Using radon as environmental tracer for the assessment of subsurface Non-Aqueous Phase Liquid (NAPL) contamination – A review. *Eur. Phys. J. Spec. Top.* 224, 717-730.

Voltaggio M. & Spadoni M. (2013) - Determination of <sup>222</sup>Rn in water by absorption in polydimethylsiloxane mixed with activated carbon and gamma-ray spectrometry: An example application in the radon budget of Paterno submerged sinkhole (Central Italy), *Applied Geochemistry*, 34, 65-74.

## **Effect of material heterogeneity and environmental humidity on the stability of gypsum in underground quarries**

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*Keywords:* creep, gypsum rock, relative humidity, microstructure.

The realization of tunnels, boreholes or quarry drifts in evaporite terrains often brings to face issues related to the geological and physical peculiarities of these rocks. In particular, typical problems are caused by the swelling behaviour of anhydrite, the high solubility in water and the high heterogeneity of gypsum facies. All these problems are particularly evident in the framework of quarry exploitation: the stability of rock pillars in underground quarries requires dedicated investigations. This study proposes an analysis of the main parameters that may affect the stability of underground gypsum pillars, considering in particular the effect of material heterogeneity and relative humidity. With this aim, the study proposes an investigation of a strongly heterogeneous facies of gypsum from the Messinian Salinity Crisis (i.e. branching selenite facies from Monferrato area, NW Italy). The textural and microstructural heterogeneity of the material is described with different techniques (MIP and SEM analyses). The study then includes a series of ad hoc designed mechanical tests to quantify strength and creep in function of the relative humidity. Results show the clear influence of material heterogeneity on the mechanical response. To this intrinsic mechanical variability, the influence of an external parameter as the humidity is observed to generate an additional reduction of material strength and to increase the creep strain rate in the long term tests. The effect of all these elements in the framework of a real underground quarry site is eventually discussed.

## Using digital pore-scale image analysis to assess subsurface carbon storage reservoir potentiality

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Keywords: CT images, CO<sub>2</sub> storage, pore-scale analysis, reservoir.

The growing importance of subsurface carbon storage for tackling carbon emissions requires an accurate characterisation of potential reservoirs to understand their capabilities. A suite of sandstone samples has been characterised at the micro-scale using micro-computed tomographic imaging. We investigate how pore and grain geometries control crucial features of a suitable reservoir such as porosity and permeability. Studied samples are from sites located in suitable geographic locations which could be beneficial to the growth of CCS in the UK (Payton et al., 2021). These include (i) the UK Geoenergy Observatories (UKGEOS) Glasgow observatory from the Upper Carboniferous Scottish Middle Coal Measures Formation, (ii) the laterally equivalent facies of the Sherwood Sandstone Group to the UKGEOS Cheshire observatory from drilling at Sellafield (Cumbria) and (iii) core material from offshore reservoir targets as potential CO<sub>2</sub> storage. Results show porosity values between 0.04 and 26.4% and permeabilities of up to 6000 mD. Based on these results, we are able to make recommendations for further study at sites showing favourable characteristics for subsurface storage. We also identify and constrain a percolation threshold of ca. 10% total porosity, which is shared between sites, above which near full pore connectivity is observed. Results from this study can be applied to other localities and reservoir intervals suitable for CO<sub>2</sub> storage. In particular, they can be used as a measure of reservoir suitability when making initial assessments of storage reservoirs without the need for expensive and time-consuming analyses.

Payton R., Fellgett M., Clark B., Chiarella D., Kingdon A. & Hier-Majumder S. (2021) - Pore Scale Assessment of Subsurface Carbon Storage Potential: Implications for the UK Geoenergy Observatories Project. *Petroleum Geoscience*, 27, petgeo2020-092, <https://doi.org/10.1144/petgeo2020-092>.

## **Recycling of granite scraps in Sardinia by innovative and economically-viable extraction technology in a context of circular economy**

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*Keywords:* feldspar production, waste management, soil consumption.

Italy is the world's second-largest feldspar producer (3 million tons/year, 22% of total) and the world biggest importer (22% of global world trades) (European Commission). Since the strong demand is rapidly depleting the proven reserves in EU Member States, the EU ceramics sector is increasingly dependent on feldspar imports from Turkey. In the future, it will be necessary to find additional sources of feldspar or to further increase inter-continental transport. The ever-increasing demand for feldspar, for ceramics, glass and other industrial uses, therefore, requires the extraction of granite and considerable international trade flows. At present, Buddussò-Alà dei Sardi (Sardinia Region-Italy) is the most important granite production area in Italy, with 66 authorised quarries (12 active), 70% of regional granite production and more than 50% of total Italian production. However, granite mining activities cause serious environmental problems. In Italy, every year 350.000-400.000 m<sup>3</sup> of raw granite are extracted (Lucarini et al, 2020) generating the same quantity of waste. Feldspar production and trade generate large amounts of pollutant and greenhouse gas emissions, due either to the energy consumption of mining activities or from the transport of the finished product from the exporting countries (mainly Turkey and China). The areas where quarries are active suffer from landscape degradation, due to incomplete compliance or non-compliance with quarry recovery plans, considering that opening new quarries is cheaper than moving large amounts of waste. Finally, granite mining accounts for huge amounts of soil consumption, as it requires large areas in which the quarry waste accumulates.

The LIFE REGS II project (LIFE19 ENV/IT/000373 LIFE REGS II) aims at demonstrating an innovative and economically-viable extraction technology to produce feldspars, of the same quality to those obtained from virgin raw material, using granite scraps rather than virgin raw material. This will reduce demand for feldspar from environmentally-damaging granite mining operations as well as to minimize the soil consumption and to boost the awareness about the importance of recycling granite scraps.

The project will contribute to the implementation of the EU Action Plan for the Circular Economy, the Roadmap for a Resource Efficient Europe, and Directive 2006/21/EC on the management of waste from extractive industries.

European Commission, Study on the EU's list of Critical Raw Materials (2020) - Factsheets on Non-critical Raw Materials. Lucarini M., Carta R., Fumanti F., Martarelli L. & Serra M. (2020) - "The Italian Database GeMMA: from monitoring production to cataloguing mining wastes, a starting point for recovering critical raw materials from abandoned mines?" in European Geologist Journal 49 Mineral raw materials in Europe – Chances and challenges for domestic production.

## **Defining the shallow geothermal potential by using the seismic microzonation data: a case study from the Southern Marche Region to encourage a sustainable post 2016-earthquake reconstruction**

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*Keywords:* shallow geothermal energy, ground source heat pump, thermal conductivity.

The use of renewables is of paramount importance for sustainable development and economic growth. In this context, shallow ground-sourced heat exchangers (*GSHEs*) coupled with geothermal heat pumps represent a valuable opportunity for heating and cooling systems both in urban and rural areas. The regions of the Central Italy affected by the 2016 seismic sequence ( $M_{\max}$  6.5), while involved in the post-earthquake reconstruction, could greatly benefit from the installation of *GSHEs*, which are environmental-friendly and with two peculiarities among the renewables: (i) continuous source of thermal energy and (ii) landscape protection (*GSHEs* are not visible). Here the focus is set on the evaluation of the shallow geothermal potential for the southern sectors of the Marche Region, with the aim of producing maps favouring the knowledge of the heat that could be extracted through *GSHEs* from different rocks of the subsoil. As a first pilot area we selected the upper-middle portion of the Potenza river fluvial plain to quantitatively estimate the values of key parameters such as the thermal conductivity, the volumetric heat capacity of the subsoil and the specific heat extraction. We followed the methods described in Taussi *et al.* (2021), thus averaging the geothermal parameters values over the first 100 meters, *i.e.* the most common depth of *GSHEs*. In order to assign the representative values for the shallow heat exchange parameters, the local stratigraphy was reconstructed on the basis of the surveys and data (mainly geognostic drillings) made available by the Civil Protection, thanks to the completion of the third level of the seismic microzonation studies. This freely accessible database might represent a valuable tool and source of information for such shallow geothermal studies in many different areas, and thus we recommend its use, given the relatively easy availability. In addition, the possibility (and the reliability) to use geophysical surveys (such as MASW or HVSR analyses) data, typically available in such databases, will be tested in order to independently estimate and compare the values of the most relevant shallow geothermal parameters. Preliminary results indicate that higher values for thermal conductivity ( $> 1.9 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) and volumetric heat capacity ( $> 2.35 \text{ MJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$ ) characterize the uppermost sector of the fluvial plain of the study area, especially those areas around San Severino Marche and the ridges corresponding to Treia and Pollenza, where the, respectively, carbonate and siliciclastic bedrocks occur at relatively shallow depths. The development of *GSHEs* for heating and cooling systems should be really regarded as an opportunity for the reconstruction of these areas hit by the 2016 earthquake.

Taussi M., Borghi W., Gliaschera M. & Renzulli A. (2021) - Defining the Shallow Geothermal Heat-Exchange Potential for a Lower Fluvial Plain of the Central Apennines: The Metauro Valley (Marche Region, Italy). *Energies*, 14(3), 768.

## Status and perspectives of monitoring induced seismicity in Italy

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Keywords: induced seismicity, seismology, energy.

As demand for energy — and corresponding concern for the impacts of associated technologies — keep growing, the possible geological effects of underground anthropic activities is a topic receiving increasing interest in society and science alike. In Italy, the 2012 Emilian earthquake sequence marked an important step on this regard, as it raised suspicion that it could be related to extensive hydrocarbon extraction and storage in the region. The International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Region (ICHESE), nominated by Ministero dello Sviluppo Economico (MISE, the relevant national authority) following requests from the local government, wrote recommendations for implementing continuous geophysical monitoring of underground energy technologies. Such recommendations resulted in guidelines (Indirizzi e Linee Guida per il monitoraggio della sismicità, delle deformazioni del suolo e delle pressioni di poro nell'ambito delle attività antropiche, ILG; Dialuce et al., 2014) issued by the Direction for safety of mineral and energy activities, DGS-UNMIG, of the MISE. INGV has been involved in a few test implementations of the ILG (Braun et al., 2020) from which we may draw some considerations. In Italy, hydrocarbon extraction does not appear to have increased seismicity (Garcia et al., 2021). Re-injection of produced water can cause changes in mechanical properties of the nearby crust, but such changes are small and rather elusive (Berbellini et al., 2021). Besides, application of the ILG need to address some critical issues (Braun et al., 2020), among which inherent uncertainties of hypocentral location (Garcia-Aristizabal et al., 2020).

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## Geomanifestations in the Pannonian basin as an indicator of deep structures and geothermal potential

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*Keywords:* thermal water, geothermal potential, structural framework, fault zone.

The Pannonian Basin is a transboundary Neogene basin system on the top of a complex Paleo-Mesozoic crystalline and sedimentary sequences. It is well known for its geothermal potential. Within our latest research in the GeoConnect3d project, we tested whether geothermal anomalies and other so-called geomanifestations in a case study of the Mura-Zala sub-basin confirm the evolved structural-geological model.

The concept of geomanifestations was introduced by R. Barros and K. Pissens in 2020 within setting the methodology for two-step structural framework and geomanifestations identification and is used “to define any distinct local expression of ongoing or past geological processes”.

In the Mura-Zala sub-basin, extending between Slovenia, Croatia and Hungary, we found 9 wells with convection cells, 8 mofettes, 8 natural mineral waters, 6 mineral waters, 22 thermal and 17 thermomineral waters/sites. Mineral occurrences are rare, only 4. Organic matter occurs at 78 coal sites, 1 oil spring, 5 gas fields, 6 oil fields and 17 oil and gas fields. Mantle helium exhalation is evident at 17 sites.

We were able to link fault zones to geomanifestations. Along the Ljutomer fault zone we interpreted convection cells causing geothermal anomalies, seismic activity, and structural traps resulting in hydrocarbon accumulations. Along the Raba fault zone we interpreted convection cells causing geothermal anomalies, some seismic activity at its western part, mineral and thermomineral waters, and CO<sub>2</sub> and mantle helium exhalations. And along the Periadriatic fault system, where the Labot and Šoštanj fault zones join, we identified seismic activity, mineral and thermomineral waters, and CO<sub>2</sub> and mantle helium exhalations.

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## **A comparison of three recent drilling projects in unconventional geothermal resources in the Phlegraean Fields Caldera, the Cornubian Batholith, and the Williston Sedimentary Basin**

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*Keywords:* CFDDP, DEEP, UDDGP, geothermal energy, Campi Flegrei Caldera, unconventional energies.

In recent decades, numerous advances have been made in the study of geothermal potential in volcanic and non-volcanic areas on a planetary scale. One of the first effects of such studies have been the exploitation of clean energy resources in areas of high volcanic risk and in densely populated areas.

The growing demand for clean energy, particularly in developing countries, has become an objective of primary importance today. In this regard, characterize geothermal reservoirs as low/intermediate temperature resources (for heating and cooling of buildings, district heating and solar energy) or as high temperature resources (for electricity generation or co-generation). Characterization of high-temperature geothermal resources captured through deep wells (1-5 km) drilled to reach reservoirs, may be located in highly heterogeneous volcanic complexes, sedimentary basins or old bedrock. Reservoir permeability can be increased through various engineering techniques to improve productivity, although such techniques can raise difficult issues of social acceptability. Low- or medium-temperature resources are exploited within shallow (a few meters) or intermediate (up to 1 km) wells and primarily provide heating and cooling capabilities. In recognition of these conditions, the development of a robust interdisciplinary methodology to characterize such geothermal systems from volcanological, geophysical, geochemical, and geo(hydro)thermal perspectives is critical.

In this study we review in detail the results obtained during three recent drilling experiences focused on the characterization of unconventional resources: the Campi Flegrei Deep Drilling Project (CFDDP) in Italy, the United Downs Deep Geothermal Power (UDDGP) project in the United Kingdom, and the DEEP Earth Energy Production in Canada. The main aspects of each project are described (geology, drilling, data collection, communication strategies) and compared to discuss challenges encountered at the three sites considered, including a scientific drilling project (CFDDP) and two industrial ones (UDDGP and DEEP). The first project, at the first stage of the pilot hole, although not reaching deep supercritical targets, showed extremely high, very rare thermal gradients even at shallow depths. Although each project has its own history, as well as social and economic context, the lessons learned at each drilling site can be used to further facilitate geothermal energy development.

## Energy transition and reuse of oil and gas wells as deep enhanced closed loop geothermal heat exchangers: the Padova area (Italy) case study

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*Keywords:* deep ground closed-loop, exhausted or barren oil and gas well, geothermal energy, heat transfer process, numerical simulation.

Since the 1950s many sedimentary basins worldwide and in Italy were highly explored for oil and gas exploitation, CO<sub>2</sub> sequestration, geothermal and mining applications, providing an accessible deep underground database and a number of exhausted wells currently not used. Just in Italy, since the beginning of 20th century, more than 2000 exploratory wells were drilled, mainly for hydrocarbon exploration and abandoned (ViDEPI Project).

A promising option for the reuse of these abandoned wells, characterized by great depth (usually > 1 km) and high underground temperatures, is to create a deep-closed geothermal loop by the underground connection of two near wells with multilateral wells (Kharse et al., 2019). In this way, the geothermal heat naturally available underground could be exploited by the circulation of an operative fluid inside the wells (closed loop). The simplicity of this approach means that no aquifer is involved and that the systems can be constructed almost anywhere making geothermal energy scalable and available for local communities, favoring the energy transition towards renewable energies (Winsloe et al., 2020). This will boost geothermal energy use contributing to increase its share in the total energy produced in Europe by 2050 (Dalla Longa et al., 2020).

In detail this work aims to analyze the feasibility in terms of heat and power production of a closed circuit involving the wells Legnaro and Piove di Sacco located in Padova territory, in an area characterized by a normal geothermal gradient.

At first the wells stratigraphies and thermal properties of the main lithologies were defined. Then, several numerical simulations of the closed loop were carried out in steady state, to define the laminar flow and the heat transfer in the rocks and the circulating fluid. In detail the possible effect on power and heat production due to the variation of (i) wells vertical depth, (ii) horizontal connection length, (iii) geothermal gradient, (iv) rocks thermal conductivity and (v) carrier fluid flow rate inside the closed loop probes were considered.

The results obtained allow to point out the pro and cons of the proposed approach for heat and power generation in abandoned wells, highlighting also possible solutions to implement the heat extraction.

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## **S9.**

# **Hydrogeological environments: challenges and advances**

*CONVENERS AND CHAIRPERSONS*

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*Manuela Lasagna (University of Torino)*

*Franci Gabrovsek (Research Karst Institute Postojna)*

## **Groundwater asbestos contamination in Naturally Occurring Asbestos (NOA) rich areas: a study on fibres characteristics, concentration and their possible mobility in aquifers**

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*Keywords:* groundwater, flow model, hydrogeology, NOA rocks, asbestos.

In Naturally Occurring Asbestos (NOA) rich areas, weathering and erosion of asbestos-bearing rocks (e.g. meta ophiolites) are likely to cause water asbestos pollution: this may occur as a consequence of superficial and groundwater flow through natural rock formations containing NOA, depending on the characteristics of either the rocks and hence the water.

Concerning groundwater management in NOA settings, asbestos pollution has to be considered with regard to water quality assessment: it represents an environmental problem and could even constitute a risk for human health. In fact, waterborne asbestos can come into contact with human beings as airborne fibres after water vaporization, or by ingestion, especially if they are present in drinking water. While a lot is known about diseases caused by airborne asbestos respiration (e.g. IARC, 2012), not enough has been yet understood about potential noxiousness of its ingestion. Consequently, a Maximum Contaminant Level for asbestos in potentially usable water has not been defined yet (WHO, 2020).

To investigate possible groundwater pollution by asbestos due to natural environmental causes, a study area was selected in Piedmont, nearby NW Alps which are rich in NOA (and naturally occurring asbestiform minerals non-asbestos classified) (Belluso et al., 2019). In this area, two sampling and analysis campaigns regarding surface waters and groundwater were settled to investigate if, how and which type of mineral fibres could occur in water, trying to correlate them to the geolithological and hydrogeological characteristics of the area.

The results of the two campaigns will be presented aiming to investigate asbestos and asbestiform fibres occurrence in water in relation to hydrochemical parameters, which are expression of the local hydrology and geolithology, and to evaluate seasonal variability. In addition, asbestos (and asbestiform) fibres transportation due to water flowing in NOA settings will be tested with a physical model, since a recent study highlighted possible asbestos mobility through soil (Mohanty et al., 2021): guidelines to create a flow model which describes mineral fibres mobility in porous aquifers will be presented following laboratory tests based on contaminated water circulation through packed columns.

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## **An adaptation plan for the salt water intrusion into the coastal aquifer of Fano (PU, IT): management of risk in sea level rise scenarios (EU Interreg Asteris Project)**

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*Keywords:* adaptation plan, monitoring transects, salt intrusion.

The North-Adriatic Sea level rise caused by the climate change in progress and the results of a risk analysis of salt water intrusion (SWI) in coastal aquifers, at regional and local scale, are the output of an EU project named ASTERIS (Adaptation to Saltwater inTrusion in sEa level RIse Scenarios) co-funded by Interreg Italy-Croatia Cross Border Cooperation Programme.

In order to reduce the environmental and socio-economic losses due to the progression of foreseen salinization along the coastal aquifer in the municipality of Fano (PU – Marche region, Italy), an adaptation plan has been built. The municipal adaptation plan matched the actions to be followed, in terms of sustainable use of groundwater resource, designed to maintain the interface between fresh and salt water toward the sea, re-orienting the pumping systems, lowering the interface zone and creating barriers to SWI. The envisaged adaptation measures are organized according to the hydrogeological effects in different zones of the coastal aquifer and are related to group of stakeholders, planning key-roles in the use of the groundwater resources. A particular focus has been dedicated to surface water bodies into the city, in direct connection with seawater, that shows higher EC values, which denoted the presence of seawater ingression along the riverbed. With reference to the temporal variations of the salt intrusion process, the “dynamic updating” of the adaptation plan seems to be the best method, supported by field observation. For this reason, have been suggested some test sites (“monitoring transects”) that could be provided by installations of monitoring devices, distributed between the emerged beach and the inland.

A wide spectrum of measures has been proposed, according to a specific land-use settings and to a “vulnerability zoning” criteria, among which:

- preventive measures in low-vulnerability coastal areas, in order to delay salinization;
- mitigation measures in medium-vulnerability coastal areas, accepting the idea of a certain degree of salinization of the coastal aquifer, trying to obtain a reduced impact on the socio-economic and environmental system, through limitation of total damage;
- recovery/contrast measures in high-vulnerability coastal areas, trying to minimise the impact affecting the socio-economic and environmental system involved by the groundwater salinization.

The “Adaptation plan” for the Municipality of Fano must be based on the existence of a control room, oriented to the coastal aquifer system management, with the aid of a numerical forecasting simulation model of flow and salt transport into the coastal aquifer, able to assess and predict SWI evolution; its purpose is to ensure support for the Strategic Planners in order to implement a combination of prevention, mitigation and remediation measures in urban, agricultural and natural contexts.

## **Preliminary hydrogeological study of the Rosarno Plain in the sector between Nicotera and Gioia Tauro (Calabria - Southern Italy)**

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*Keywords:* Rosarno plain, lithostratigraphic data.

The study area lies in the Rosarno/Gioia Tauro alluvial plain, a tectonic depression generated mainly by the normal faults of “Nicotera” [direction WNW-ESE] and “Cittanova” [direction NE-SW], (Ghisetti, 1979; Tortorici et al. 1995, 2002). The Nicotera fault crosses N the study area, the Cittanova fault runs E, outside the study area. The acquisition of lithostratigraphic data and static groundwater levels allowed to carry out this preliminary hydrogeological study that, in the final version, aims to implement the knowledge shallow aquifer of the selected area.

The lithology, derived from the Geological map of Calabria (CASMEZ, 1967), consists of:

-Alluvial complex (medium permeability): gravelly-sandy and conoid deposits of heterogeneous granulometry with prevalence of sandy terms;

-Sandy-gravelly-conglomerate complex (medium-high permeability): continental deposits of terrace, of Heterogeneous granulometry, moderately thickened;

-Igneous complex (low permeability which increases in relation to the fracturing index): acidic granite rocks which often present, on the surface, a blanket of alteration, that may locally be the site of limited aquifers.

The lithostratigraphic data show that the shallow aquifer, in the study area, is located in alluvial/terrace complexes, characterized by medium-high permeability due to the granulometric heterogeneity distinguishing them. Interpolating the available static levels, the preliminary piezometric map of the area was derived using an “ordinary kriging”, given the non-homogeneous distribution of the measurement points. The piezometry is between 30 m asl (innermost sectors) and 0.5 m asl (along the coast), with a general out flow from E to W. By interpreting the piezometric morphology, underground water sheds and prevailing flow directions were traced. Among the latter, the most evident corresponds to the bed of Mesima river. In the inner zones, the isopiezometric line shave a lower distance between them, this shows short hydraulic paths and high hydraulic gradients. In the external areas, the distance between the isopiezometric lines is wider, this translates into a greater hydraulic path and a lower hydraulic gradient. Therefore, according to the state of knowledge, the inner most areas, corresponding to faster aquifer sectors, represent the recharge areas, while the external areas, corresponding to slower aquifer sectors, constitute the drainage areas.

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## Hydrogeological setting of the multilayer aquifer of S. Eufemia Lamezia Plain (Calabria)

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Keywords: S. Eufemia Lamezia Plain, multilayer aquifer.

The studied plain lies in the Tyrrhenian sector of the “Graben of Catanzaro” (Amodio Morelli et al., 1976) generated by sub-vertical faults with a left lateral strike-slip component (Gulla et al., 2005). Lithostatigraphic/hydrogeological data show a multilayer aquifer, separated by clave horizons (Cuiuli 2012, 2015, 2018). The phreatic aquifer is located in the alluvial deposits, the artesian aquifer is in the sands and sandstones, while the third aquifer appears to be hydrothermal, from the available data. The feeding of the aquifers is carried out by direct recharge in the shallow aquifer, lateral recharging in the intermediate one, rising fluids through the fractures of the bedrock in the deep aquifer. The piezometric map of the shallow aquifer (Cuiuli, 2012), show a drainage area along the coast and an internal recharge area. The main drainage axis coincides with the Amato river. For the shallow aquifer, the clayey substrate map was also derived (to evaluate the deep [b] of the aquifer) and the hydraulic parameters were estimated: Transmissivity [ $T=1.22 Q/\Delta S$ ] (Celico, 1986); Permeability [ $K=T/b$ ], Storage Coefficient [ $S=3 \times 10^{-6}b$ ] (USGS, 1975). The hydraulic gradient [ $i$ ] was defined graphically from the piezometric map. The hydraulic parameters vary from the hinterland towards the coast ( $1,0 \times 10^{-3} > T > 1,8 \times 10^{-2}$  [m/s];  $9,0 \times 10^{-5} > K > 7,2 \times 10^{-4}$  [m/s];  $9,0 \times 10^{-6} > S > 1,5 \times 10^{-3}$ ;  $3 > i > 0,8$  [%]), probably due to the granulometric heterogeneity and the variation in thickness of alluvial lithotypes. Instead, for the second aquifer, the sand/sandstone top map was built, showing a more productive area, along the coast, delimited by 3 faults determining the greatest depth with respect to the context. All maps were built with an “ordinary Kriging”. Therefore, this work aims to contribute to the hydrogeological knowledge of the aquifer studied, in support of studies oriented to the protection and management of the resource in terms of safe guarding and planning its use.

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## **A multidisciplinary approach to outline natural and anthropogenic groundwater contamination (case studies in central and southern Italy)**

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*Keywords:* groundwater monitoring, groundwater contamination, redox processes, natural background concentration, Central and Southern Italy.

The water–rock interaction is discussed in this study for two sample areas with alluvial aquifers in central and southern Italy, where there were observed a groundwater contamination by nitrate and metals (Iron and Manganese).

Thanks to a multidisciplinary approach based on a seasonal monitoring of hydrogeological, hydrogeochemical and isotopic variables, to a spatial and time series statistical approaches and to a detailed geological analysis, it was possible to demonstrate that the hydrogeological setting is potentially able to generate natural contamination, sometimes over the Concentration Limit of Contamination (in coherence with the EU and Italian regulations).

The results suggest that more detailed hydrochemical monitoring, statistical and geological studies are required for areas where lithologies with fossil organic components are present. Insights should further investigate the interaction between groundwater and rocks in terms of organic compounds as well as inorganic compounds. In particular, the study also suggests that the insights on redox balances in groundwater are needed especially in the area where anthropic contamination by organic substances are present. The study also verified the effectiveness of the groundwater monitoring network, the present distribution of nitrate and metals in groundwater and the evolution of these trends at different scale: regional, groundwater body and single well.

In some cases, these results highlight the need to assess the natural background concentrations and possibly raise the threshold values.

## The impact of climate change on groundwater temperature of the Piedmont Po plain (NW Italy): preliminary results

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*Keywords:* groundwater temperature, trend, climate change, Po plain.

It's now recognized that a global climate change is taking place, leading to an increase in temperatures and a variation in precipitation regime, also affecting groundwater (GW) (Taylor et al., 2013).

In this study we want to evaluate how climate change affects GW temperature in the Piedmont Po plain (NW Italy).

The Piedmont Po plain covers the 27% of the whole region and it's the most important GW reservoir of the Piedmont region (De Luca et al., 2020). It consists, from top to bottom, by Alluvial deposit complex (lower Pleistocene-Holocene), that hosts a shallow unconfined aquifer, the "Villafranchiano" transitional complex (late Pliocene-early Pleistocene), that hosts a multilayered aquifer, and a Marine complex (Pliocene) hosting a confined aquifer (De Luca et al., 2020).

For this research, 41 wells in the shallow aquifer and 20 weather stations were selected throughout the Piedmont Po plain area, and GW and air temperature parameters were analysed for the period 2010-2019.

The GW temperature data were firstly studied with basic statistical analysis (mean, maxima, minima) and then with the Mann-Kendall and Theil-Sen methods to evaluate the trend of the monthly mean GW temperatures. GW temperatures show a general increase in all the plain, up to a maximum of 2.18 °C/10 years. The same analyses were carried out for the air temperature data and it was observed that the increases vary between 1.52 and 2.11 °C/10 years.

Then to compare water and air temperature, the Voronoi polygons method was used on QGIS by centring the polygons on the weather stations. From this comparison, it was possible to highlight that in most cases (37 on 41, thus 90% of the analysed couples of temperature data) there is a greater increase in the monthly mean air temperatures than in the monthly mean GW temperatures.

The same behaviour was observed for the monthly minima and maxima GW and air temperature.

These results testify a greater resilience of GW temperature to climate variability. Future insights will be a detailed analysis of the factors influencing the more or less evident increase in GW temperatures in relation to air temperatures (e.g. depth of the water table, position of the monitoring well, position of the probe inside the well...).

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## Hydrogeological map of the Southern mountainous portion of Marche Region (Central Italy)

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*Keywords:* hydrogeological mapping, mountainous aquifers, Marche Region, central Italy.

Hydrogeological mapping represents an essential tool for groundwater resources management and to study regional-scale variations induced by anthropic pressure, climate change, and catastrophic natural events. The mountainous aquifers, in particular, represent the natural water towers of our planet. The Water Framework Directive 2000/60/EC establishes the action of water policy for the European Community. According to that, many water protection and management plans have been developed by the local authorities aiming at achieving the quali-quantitative targets for the protection of water resources and water bodies, ensuring a long-term sustainable water supply. The authority's decisions are supported by hydrogeologists, with maps focusing on the main hydrogeological complexes of the national and local territories. For these purposes, a new regional-scale hydrogeological map has been realized regarding the southernmost mountainous part of the Marche Region, considering both the fractured carbonate reliefs of Sibillini Mts. and the "Laga" geological formation. This map extends from the upper portion of the Chienti river basin to the Tronto river basin and integrates both the discharge measurements conducted during the years and the information from different kind of maps, i.e. the official geological maps of Marche Region and other published maps (Pierantoni et al., 2013; Viaroli et al., 2021). The major tectonic lineaments have been interpreted from a hydrogeological point of view and reported on the map. Based on detailed geo-structural fieldwork performed in the area and on the available literature, the geological formations have been reclassified into homogeneous hydrogeological complexes. Operating in a GIS environment, they have been merged to obtain hydrogeological complexes. The boundaries of these complexes lying below the Quaternary deposits have been inferred. The main punctual and linear springs of the area have been included in the map. Spring discharge has been measured using both hydrometric current meters and artificial tracers and they have been added to the discharge data provided by drinking water companies of the area. The new map can be used as a visual decision support tool to evaluate water resources in these highly productive but relatively unexplored areas and will provide an updated database on water resources availability to the Marche Region and other public authorities.

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## Geochemical characterization of the Timau Karst aquifer

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*Keywords:* hydrogeology, stable isotopes, tritium, tracing test, precipitation, spring, geochemical monitoring network, karst aquifer, karst spring, Fontanon di Timau, Alta Valle del But.

The north-western sector of the Friuli Venezia Giulia Region, on the border between Italy and Austria, is characterized by the presence of an extensive mountain massif where outcrop the intensely karstified Devonian limestones.

The high average rainfall, together with the high permeability of carbonates, has favored the development of an extensive aquifer, the main source of which is represented by the Fontanon di Timau. Due to its high flow rate, between 250 and 5000 l/s, the spring is exploited both for the supply of drinking water and hydroelectric energy. Given the importance of the source, a research project has started, partially funded by the Geological Service of the Friuli Venezia Giulia Region, aiming at the hydrogeological characterization of the survey area in order to identify the its recharge area and evaluate its vulnerability.

The present paper proposes a hydrogeochemical characterization of precipitation, surface waters and springs in the area located between Mt. Coglians and the Alta Valle del But, and between Eiskar glacier, the valley of the Valentina and the Anger valley for the Italian and Austrian sectors, respectively.

The study was carried out over a period of about 5 years, during which a hydrogeological survey was carried out in order to identify all the sources present in the area and to design a geochemical monitoring network of the waters. Thanks to special rain gauges, monthly precipitations were collected for the isotopic composition analysis in order to determine the isotopic gradient of the area (Plocken, Mt. Croce Carnico, and Rivo). Surface and spring water samples were collected for the study of stable (O and H), unstable (3H) isotopes, radionuclides (Rn), major and trace elements. The trends related to the temperature and electrical conductivity of the water in correspondence of different sampling points were also defined.

At the same time, tracing tests were also performed using uranine and tinopal, which made it possible to verify the hydrogeological connection between the western sector of the karst area and the Fontanon di Timau and to define the hydrodynamics of the underground system.

Isotopes and trace element results highlighted that Fontanon di Timau spring is significantly fed by the massif of Mt. Coglians-Creta di Collinetta as well as by the waters that infiltrate the area of Pal Piccolo-Creta di Timau and partially also from the waters that infiltrate beyond the watershed in Austrian territory. All the other springs identified in the area, on the other hand, have much lower flow rates and drain waters from neighboring basins limited to the Italian side only.

## Identifying areas suitable for Sustainable Drainage Systems and Aquifer Storage and Recovery to mitigate stormwater flooding phenomena in Rome (Italy)

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*Keywords:* urban hydrogeology, SuDS, ASR, stormwater flooding management.

This study proposes a survey methodology for identifying areas for combined Sustainable Drainage Systems (SUDS) and Aquifer Storage and Recovery (ASR) (Dearden et al. 2013, Sharp Jr., 1997); these techniques exploit the hydrogeological and geomorphological characteristics of an area, to increase the natural infiltration capacity of water into the ground.

The target area is the city of Rome and the aim of such techniques is to solve the problems related to rainwater which, in case of extreme events, struggles to infiltrate the ground, overloads the undersized hydraulic systems and floods the urban space.

The proposed method involves GIS geospatial analysis of various data: the permeability of outcropping lithology, the piezometric level of the aquifer, hydrogeological units, geomorphology and land use.

To identify the suitable areas, areas characterised by high permeability and a piezometric level that would confer a volumetric capacity to possibly store even large quantities of water, without triggering possible problems associated with fluctuations in the water table, were identified.

The data were divided into classes and indexed in order to compare and overlap them. Finally, hydrogeological units were also taken into account (by analysing their depth trend) in order to identify areas with similar characteristics of permeability with respect to depth. The latter will also be compared with the previous data to identify the areas suitable for SUDS and ASR.

The final product of the suitable areas from a hydrogeological point of view will be compared with the land use map in order to exclude those areas that, for administrative and other legislative reasons, cannot be destined to this kind of activities.

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## **Application of different statistical methods for analysis of groundwater levels in time: spatio-temporal analysis in Piedmont plain (NW Italy) and comparisons with rainfall time series**

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*Keywords:* groundwater levels and rainfall time series, trends, change-points, percentiles and groundwater level anomalies.

Monitoring and analysis of groundwater levels in space and in time is one of the tools to evaluate the quantitative status of groundwater resources and identify the groundwater response to climate variability, possible alterations and critical cases (IAH, 2016).

In this study daily groundwater levels (GWL) in 36 piezometers of the shallow unconfined aquifer, and rainfall (R) data of 26 rain gauges located in the Piedmont plain (western Po Plain, NW Italy) were collected in 2002-2017 interval and analyzed. Monthly and yearly aggregated data were then elaborated.

Four methods for the analysis of groundwater resources status were applied to GWL: trends identification with the application of the non-parametric Mann-Kendall test, change-points research with the application of Pettitt test, percentiles method proposed by ISPRA (ISPRA, 2017) and non-standardized anomalies analysis. The same analysis were applied to R time series. For GWL and R time series, correlations with monthly lags and coefficient of variation of the maximum annual fluctuations, were also evaluated.

The application of different methods to the GWL series permitted to clarify the GWL evolution in time and the spatialization of results allowed us to identify four areas with a similar hydrodynamic behaviour and resource status: south-eastern sector (Alessandria plain), north-northeast sector (Vercelli-Novara plain - rice fields), western sector (Turin plain) and south-west sector (Cuneo plain).

Furthermore, the most critical areas were identified and some potential factors (anthropic, geological and hydrogeological) conditioning the hydrodynamic behaviour of the water table levels were highlighted. All the methods identified a critical situation in the Alessandria plain.

In addition, the comparison between R and GWL results provided information on the timing and pattern of aquifer recharge, the hydrodynamic behaviour of GWL and their link with R variability.

At last, this multi-criteria approach allowed to highlight advantages and limits of the applied methods.

Finally, the application of different methodologies made it possible to evaluate not only the state of the resource by highlighting possible trends and critical situations, but also the real impact of rainfall variations on GWL variations and to assess how and with what delay GWLs respond to rainfall.

Future insights will analyse the effects of other natural factors (air temperature, evapotranspiration, snowmelt) and anthropogenic variables (extent of withdrawals), with an in-depth analysis of the local hydrogeological and geological characteristics of aquifers.

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## A multi-isotope (O, H, B, Sr) approach for identifying salinity contamination along the coastal sector of Murgia aquifer (Apulia, Southern Italy)

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**Keywords:** salinization, boron isotopes, coastal aquifer, strontium isotopes, Murgia, paleo-seawater, water-rock interaction.

The analysis of pressures and impacts on the Apulian aquifers, as required by the EU WFD, has evidenced physical and chemical parameters related to groundwater salinization, particularly along the coastal strip. Predisposing factors such as lithology, tectonic evolution, aquifer over-exploitation (Passarella et al., 2017), and the ongoing climate change are various. Therefore, distinguishing natural from anthropogenic sources of salinization becomes a fundamental issue for assessing the aquifer's chemical status. In this framework, isotopic measures of O, H, B, and Sr, suitably support distinguishing different sources of salinity, water-rock interaction processes, and the origin of the water molecules (Pennisi et al., 2006). This study focuses on the coastal sector of the Murgia aquifer located on the Adriatic side of the Apulia region (south Italy). It is made up of several hundred-meter-thick Mesozoic calcareous and calcareous-dolomite rocks affected by fracturing and karst phenomena. The aquifer is confined and characterized by irregular geometry. Groundwater flows to the sea where it rises in numerous coastal springs. Paleo-seawater as an additional source of salinity has been suggested by previous studies.

<sup>87</sup> Sr/<sup>86</sup> Sr, <sup>11</sup> B/<sup>10</sup> B, (expressed as  $\delta^{11}\text{B}$  permil),  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$  determined with overall chemistry in about 50 samples collected in autumn 2019 in the study area, range from 0.70768 to 0.70884, from +15.3‰ to +43.0‰, from -7.78‰ to -3.40‰ and from -49.50‰ to -23.30‰, respectively. The coupled chemical and isotopic approach evidenced that different mixing processes concur in the water, highlighting hydrogeologic zoning and complex groundwater circulation patterns. Some samples reveal Sr and B isotopic compositions typical of the local Cretaceous carbonate rocks implying a prolonged water-rock interaction. Chemistry and isotopes in 6 samples, where chlorine ranges from 3162 to 9684 mg/L indicate a significant contribution from modern seawater. Water's intermediate compositions are explained by a different mixing degree of known endmembers, such as meteoric, marine, and rock-interacting water.  $\delta^{11}\text{B}$  values, <sup>87</sup> Sr/<sup>86</sup> Sr ratios, and Cl, B, and Sr contents seem to exclude the contribution of fossil seawater to the studied groundwater. Further studies on high conductivity samples are ongoing to better detail the zoning based on the isotopic and hydrogeological characteristics and to confirm or deny the occurrence of fossil marine waters.

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Pennisi M., Bianchini G., Muti A., Kloppmann W. & Gonfiantini R. (2006) - Behaviour of boron and strontium isotopes in groundwater-aquifer interactions in the Cornia Plain (Tuscany, Italy). *Appl. Geochem.*, 21, 1169-1183.

## Flash flood event recorded in caves: the case of Supramonte (Sardinia, Italy)

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*Keywords:* extreme events, global changes, karst hydrogeology.

The high dynamism of karst aquifers makes them susceptible to short-term climate changes. One of the predicted consequences of global climate change is the increase of the extreme events recurrence.

To improve the understanding of its effects on the complex hydrogeology of karst aquifers, the coupled measurement of cave drip rate and spring discharge monitoring has been analysed for the intense rainfall event recorded in the Supramonte karst massif (Central East Sardinia, Italy) on 18th November 2013. During this extreme episode, more than 450 mm of precipitation fell in this area in just 12 hours, reaching a rainfall intensity of 60 mm/hour and triggering a flash flood with catastrophic consequences.

For the monitoring of such episode, drip rate monitoring was performed at the Perdeballa cave located at the boundary of the carbonate aquifer in the upstream part of the Supramonte catchment area, while groundwater discharge was measured at Su Gologone spring, the main karst resurgence located 21 kilometres downstream from the cave.

During this extreme event, cave drip rate increased from the base level of 30 mL/hour up to 480 mm/hour. At the karst spring, the peak discharge reached around 40 cubic metres per second, a value of two orders of magnitude greater than the average flow of the spring (around 200 L/s).

The lag among peak rainfall intensity, the highest cave drip rate and spring water level indicates a delay in the response time of the karst system to this more and more extreme events.

## **Evaluation of the SWAT model with respect to different variables within the Tomebamba River sub-basin belonging to the Paute River Basin-Ecuador**

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*Keywords:* Modeling, Paute, Tomebamba, Moriasi.

In Ecuador, the Paute river basin is one of the most monitored due to its importance for the generation of hydroelectric energy (Amay & López, 2015). However, in recent years there have been problems related to dry seasons that limit the distribution of electrical energy for industrial and domestic purposes (Galárraga, 2000). The ETAPA company indicates a decrease in water quality in urban areas, since measurements were made in the upstream sections and in sections of rivers that cross the city of Cuenca (occupying 41.22% of the province) obtaining data that showed that the quality indices fall from an excellent-good classification for the high sections, to a good-average classification in the low sections (Amay & López, 2015).

For this, it is essential to use hydrological simulation models in order to know the water dynamics that develops within a basin both in current and future conditions, one of them being the hydrological model known as SWAT, which was developed by the United States Department of Agriculture in conjunction with the University of Texas, whose objective is to quantify and predict the environmental impact that land use practices generate on the production of water (and its quality), sediments, nutrients and substances chemicals within a basin influenced by various factors such as the type and use of land and meteorological conditions (Ríos & Faustino, 2017).

The aim of this study is to evaluate the efficiency of the SWAT model with respect to simulations of nitrates, organic phosphorus, dissolved oxygen, sediments and evapotranspiration using as reference data observed in continuous monitoring stations. The results showed that the correlation between the simulated and the observed data is practically null if a linear relationship were established between them (Pearson's correlation coefficient). On the other hand, the simulations overestimated the evapotranspiration, dissolved oxygen and sediment values; and underestimated the values of nitrates and organic phosphorus, based on PBIAS%. The RSR statistical criterion indicates that the modeling performance is unsatisfactory for nitrates, evapotranspiration and dissolved oxygen; and it is very good for organic phosphorus and the sediments of the "Llaviuco" station, which was verified with the application of the NSE statistical criteria. It is worth mentioning that the modeling in SWAT for this case study in general can be classified as poor because an initial calibration or correction of the model was not performed.

Amay E. & López E. (2015) - Estimation of the impact of climate change on water quality for the Tomebamba River basin in Monay. Cuenca: University of Cuenca.

Galárraga R. (2000). National Report on Water Management in Ecuador. Quito: New Time.

Ríos N. & Faustino J. (2017) - Use of the SWAT Model as a Watershed Management Tool. Obtained from the Tropical Agricultural Research and Teaching Center.

## **Karst morphologies and related risks in gypsum of Monferrato area (NW Italy)**

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*Keywords:* karst, gypsum, quarries, geophysical techniques.

The circulation of karst water in evaporate terrains (e.g. salt beds, gypsum or anhydrite) may develop long circuits and important morphologies both on the surface and underground. The features of these karst circuits are strongly conditioned by the high solubility and the low mechanical strength of the rock, resulting in a high propensity to develop collapses and subsidence morphologies on the surface (e.g. sinkholes). Nevertheless, the attention of the scientific world was often more focused on karst systems in carbonate rocks that rise interest for the utility of water as drinking resource. Karst aquifers in carbonate rocks (e.g. limestones and dolomite), indeed, often represent an important source of high-quality water, while in evaporite terrains the high salinity of the water usually prevents the use of the aquifers for drinking purpose.

The investigation of karst systems in gypsum and anhydrite terrains, however, covers an important role in the minimisation and prevention of risks connected with the interference with civil infrastructures. In particular, karst phenomenon represents one of the main risk factors for the stability and safety of gypsum quarries, especially if underground. The possible filling with clay or pressurized water of the karst cavities exponentially increases the dangerousness of the phenomenon, due to swelling problems and violent water inrushes. If not carefully evaluated, the interference between karst systems and quarry activity may evolve in risk scenarios for the stability of underground tunnels and for the surrounding environment, inducing collapses of karst caves and underground quarry structures, slope instabilities, subsidence phenomena on the surface and modification of the hydrogeological setting of the area.

In this study, the features and the development of karst systems in gypsum are described and monitored in correspondence of a series active quarry sites. The karst morphologies are investigated with non-destructive geophysical techniques. Test sites were chosen in the Monferrato area that hosts some of the main gypsum bodies of Italy. The results of the geophysical investigation are integrated with the known geological features of the sites, in order to obtain a more complete and reliable description and interpretation of the phenomenon.

## Groundwater sustainability of the Isonzo aquifer

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*Keywords:* hydrogeology, porous aquifer, groundwater, sustainability.

The aquifers of the Isonzo Plain provide freshwater to more than 390.000 persons considering the towns of Gorizia (Irisacqua), Trieste (AcegasApsAmga) and part of the inhabitants of the Slovenian karst (Kraški Vodovod Sežana).

Shared between Italy and Slovenia, the Soča/Isonzo river contributes in a great measure, by streamflow losses, to the recharge of the phreatic aquifer of the easternmost part of the High Plain of the Friuli Venezia Giulia region. The adjacent karst aquifer and the artesian aquifers, the latter situated further South in the Low Plain, are dependent on this phreatic aquifer, as it provides part or most of their recharge. The area is intrinsically rich in freshwater thanks to the important precipitations (1400 mm/y), that recharge the phreatic aquifer of the High Plain by effective infiltration (4.1 m<sup>3</sup>/s), and the large hydrographic basin of the Soča/Isonzo river. Nonetheless this abundant resource seems to be declining, probably due to the combined effect of global warming, its consequent change of precipitation regime and the increased withdrawal.

Time-series data (1961-1990) of three meteorological stations ascertain an increase of temperature between 0.2 and 0.6°C per decade. Instead, precipitation data do not always show a decreasing trend (Calligaris et al., 2016; 2019).

The FVG piezometric monitoring network data show a lowering of the water table between 5 and 10 cm per year since the last 50 years (Bezzi et al., 2016). In particular, between 1985-2012, the wells of the Isonzo Plain show a decreasing trend of their level between 0.7 cm and 7 cm per year.

This lowering of the groundwater levels implies a reduction of water availability but above all a risk of degradation of the resource quality considering that the Irisacqua pumping stations withdraw phreatic waters at only 20 m b.g.l. Such shallow groundwater is highly vulnerable as witnessed by the results of ASTIS and GEP Interreg projects. The paper presents the state of the art of the knowledges in this area, keeping in mind that a further long-term monitoring is mandatory in order to assess the present and future sustainable use of the resource.

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## Tracing test in caves of Mt. Bernadia: in search of subterranean watershed

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*Keywords:* karst hydrology, cave tracing, Julian Prealps.

In the framework of the regional law L.R. 15/2016, the Dipartimento di Matematica e Geoscienze of the Trieste University and the Servizio Geologico of Friuli Venezia Giulia Region [MP1] (FVGR) joined a multi-year project for the development of a scientific protocol to identify the regional and cross-border karst aquifers. Following a hydrogeological approach, 124[MP2] karst areas were identified and outlined for a surface of more than 3000 Km<sup>2</sup> corresponding respectively to 39% of the total area and to 69% of the hilly mountain area of the FVGR. In these areas more than 28,000 epigeal karst forms (solution and collapse dolines, uvalas, poljes, blind valleys) were detected, as well as about 1,300 springs. The karst aquifers in carbonate lithologies are definitively the most abundant and several are the evaporitic ones. Julian Prealps represent a particular hydrogeological context where several megabeds of calcarenites and carbonatic conglomerates are within marls and siliciclastic sandstones of the Flysch formations (Upper Cretaceous – Eocene). Moreover two mountains (Mt. Bernadia, 878 and Mt. Matajur, 1,641 m) are tectonic wedges, composed also by Mesozoic limestone. Megabeds are highly karstified, witnessed by the presence of impressive dolines and important sub-horizontal caves draining groundwaters. The contrast between the characteristic fluvial landscape and karst features is striking. In particular, the Mt. Bernadia area, characterized by the presence of important caves in different megabeds, is bordered westerly by the Torre River and easterly by the Cornappo one. Along the water courses several are the identifiable springs. In order to better detail the outline of the Mt. Bernadia aquifer, a detailed hydrogeological survey and two dye-traces were scheduled. The experiments were realized thanks to the contribution of the speleological associations, in particular to Circolo Speleologico e Idrologico Friulano e Gruppo Speleologico San Giusto. During February 2020, in low-water conditions, the first dye-trace test started from Tirfor cave (7739/4721FR), which develops in a eocenic carbonatic megabed. Two different dyes were used: uranine was injected in the eastern branch of the cave, while tinopal was injected in the western one. Only the uranine was detected in a little stream, tributary of the Cornappo River. The experiment was repeated one year later, in the same hydrogeological conditions. Also this time, two different dyes were used, increasing the number of monitored points. Tinopal was injected in the same point as the previous year in the Tirfor cave, while uranine was injected in a westerly cave named Partigiano (2125/968FR), which develops in cretaceous limestone. Both tracers were detected along the Torre riverbed, in correspondence of different little springs, downstream Vedronza cave which acts as temporary spring. The studies realized allowed to define the groundwater watershed between the Torre and Cornappo rivers.

## Methodological study of aquifers based on integrated use, of the hydrogeological survey, radiometric analysis and field-type parametric measurements

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*Keywords:* hydrogeological model, natural radioactive tracers.

The correct management of water resources requires a good knowledge of the aquifers. The direct detection of the basic data can often be technically difficult and economically onerous. In this context, the use of natural tracers can be a valid alternative for medium-scale works. Therefore we propose a methodological study direction, based on the integrated use of hydrogeological survey [levels of groundwater, Temperature (T), Redox potential (Eh)], “activity concentration” of Radon ( $^{222}\text{Rn}$ ), and isotope ratio of the Uranium ( $^{234}\text{U}/^{238}\text{U}$ ) determined in the laboratory on sample staken. The application of the method, in the sample area, showed that the concentrations of ( $^{234}\text{U}/^{238}\text{U}$ ), ( $^{222}\text{Rn}$ ), (T) and (Eh), vary in function of the mobility water in the various sectors of the aquifer. In particular, the elaboration of thematic maps, for each indicator (piezometric and isodistribution map of the measured quantities), allows to differentiate the recharge and drainage areas of the acquirer and the preferential directions of water flow. The interpretation of the piezometric morphology, integrated with the analysis of the concentration distribution of ( $^{222}\text{Rn}$ ), ( $^{226}\text{Ra}$ ) and ( $^{234}\text{U}/^{238}\text{U}$ ), and the parametric measurements of (Eh) and (T) in the aquifer, provides information useful to distinguish: preferential directions of water flow, underground watersheds, groundwater recharge and drainage areas. It also consents to draw indications on the mobility of the groundwater in the various sectors, for the implementation of the general hydrogeological model of the aquifer studied. In particular, uranium has a different behaviour depending on the amount of oxygen present in the various sectors of the aquifer (reducing/oxidizing), while the concentration of radon activity is greater in the sectors of greater mobility of the aquifer. The measurement of the Redox Potential, on the other hand, indicates the oxidizing/reducing sectors of the aquifer, which correspond respectively, to the recharge zones and greater mobility areas of the aquifer (more oxygenated) and to the drainage zones and less mobility of the aquifer (less oxygenated). Finally, under the same conditions, the water temperature increases, due to the hydraulic path, the residence time in the aquifer and the contact times with the lithotypes that constitute it.

Therefore, this work aims to give a methodological direction for the definition of the hydrogeological model of an aquifer, based on data provided from: hydrogeological survey, parametric measurements (Eh, T), concentrations of ( $^{222}\text{Rn}$ ), Radio ( $^{226}\text{Ra}$ ) and the isotope ratio ( $^{234}\text{U}/^{238}\text{U}$ ). Each of these data provides specific information about the conditions of the groundwater which, integrated between them, with the interpretation of the piezometric map, contribute, overall, to define the general hydrogeological model of the aquifer studied.



## **Monitoring karst aquifers hydrodynamics in metamorphic carbonates: the example of the Apuan Alps, Italy**

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*Keywords:* marble karst aquifer, hydrological monitoring, dominant conduit system, water storage.

The hydrodynamic behavior of karst aquifers is usually complex due to the high degree of heterogeneity and anisotropy of their geologic and hydrogeologic properties. Among karstified rocks, metamorphic carbonate rocks (e.g marble and meta-dolostone) are characterized by very low porosity and permeability, but their hydraulic properties can be altered by geologic processes, and significant aquifers can develop into these rocks eventually. However, the functioning of metamorphic karst aquifers is still poorly known. This contribution presents the hydrological monitoring of three of the main karst springs of the Apuan Alps (Italy). This mountain chain is characterized by extensive metamorphosed carbonate outcrops in which karst aquifers have developed. Pollaccia, Renara and Equi springs were equipped with multi parametric sensors for water level and discharge (L, Q), temperature (T), and electrical conductivity (EC). Their hydrographs and chemographs were compared with precipitation time series collected by the meteorological stations to investigate the response of the karst systems to infiltration and to infer their structure. The mean discharge for Pollaccia, Renara and Equi springs were respectively about 900, 200 and 800 l/s, their EC varied between 130 and 300  $\mu\text{S}/\text{cm}$ , whereas T ranged between 7.8 and 10.6 °C. Water discharge, T, and EC response to infiltration was quick and impulsive with lag times of few hours. EC and T trends were complex for all the three springs, but dilution was the prevalent hydrodynamic response to precipitation observed during the monitoring. Piston-flow phenomena were scarce and limited to particular conditions. No delay between discharge increments and EC and T responses occurred. These observations suggest that the springs are fed by dominant conduit systems in which water flows only in few, enlarged conduits, with limited fracture storage. Piston-flow phenomena could be related to the presence of secondary flow networks that are connected with the main flow pathways only in specific conditions and/or to the flushing of limited volumes of water stored in the aquifers. Monitoring results suggest that the functioning of meta-carbonate aquifers in the Apuan Alps is controlled by several factors such as the low degree of fracturing of marbles, the local structural arrangement, and the primary porosity of the karstified rocks. As a consequence, storage is limited and flow velocity is high, preventing sustained water-rock interactions.

## Electrolytic enrichment method for the determination of tritium in aquifers: tritium as an indicator of anthropogenic pollution

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*Keywords:* tritium, liquid scintillation, electrolytic enrichment, anthropogenic pollution.

Environmental Tritium is a powerful tracer of groundwater age and it is a key tracer of groundwater movement. Consequently, monitoring of Tritium concentration in groundwater can be a very useful tool for the determination of recent exchanges with surface water and for the presence and the traceability of anthropogenic contributions.

Tritium (<sup>3</sup>H) is a radioactive isotope of hydrogen with a half-life of 12.3 years, which emits low-energy beta particles. It is a naturally occurring radionuclide through the interaction of high-energy cosmic rays with oxygen and nitrogen atoms in the upper atmosphere. The environmental levels of Tritium increased after nuclear weapon tests between 1945 and 1963, and after that it was mainly released from nuclear facilities, especially the heavy water reactor (HWR). However, Tritium concentrations in precipitation have exponentially declined over the past decades as the anthropogenic bomb tritium peak has all but disappeared. At the present, due to the natural decay of tritium and the prohibition of nuclear activities, the activity of tritium in water decreases year by year, and environmental tritium concentrations are close to natural levels of cosmic production.

To detect low concentration of tritium in water, a certain degree of enrichment is essential to obtain adequate tritium count rates, through electrolytic system. The principle of electrolytic concentration of tritium is to use the isotope fractionation effect of hydrogen isotopes in the gas and liquid phases. Water samples contain mainly HHO, HDO and some HTO molecules, so by passing an electric current through a conductive water solution, the bonds of the water molecules are broken. Discharge of hydrogen from the cathode is highly isotope-selective for protium, thus, tritium and deuterium are concentrated, leaving most of the tritium in the residual water after reduction of the water sample.

One method of <sup>3</sup>H electrolytic enrichment was developed and implemented in Italy by the ENEA's Traceability Laboratory (FSN-SICNUC-TNMT – Brasimone research center). The ENEA electrolytic enrichment procedure, which precedes the counting of tritium by liquid scintillation counting (LSC), is performed by an electrolysis system consisting of 20 steel cells, a cooling system, a temperature control unit and three multiple distillation batches for the tritium samples.

At present, given the decline in tritium activity in the atmosphere and hydrosphere, low tritium concentrations in groundwater can no longer be neglected, as they can be important indicators of anthropogenic pollutants. A good contribution to the assessment of the vulnerability of aquifers from anthropogenic impact could be offered by the determination of the low tritium in groundwater via the electrolytic enrichment methodology.

## **S10. Earthquakes and Tsunami**

*CONVENERS AND CHAIRPERSONS*

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## Historical impact and hazard assessment for tsunamis along the eastern Sicily coasts: a review

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*Keywords:* tsunami, tsunami hazard, earthquake, landslide, eastern Sicily.

Eastern Sicily is among the Mediterranean coastal regions most exposed to tsunamis. Paleotsunami databases and catalogues of historical events testify to the occurrence of several destructive tsunamis in this area, most of which connected to major earthquakes (e.g. 365, 1169, 1693, 1908) from faults in the near- and in the far-field. Different factors make the tsunami hazard assessment for the eastern Sicily coasts a very challenging topic. First of all, in the near-field the tectonic setting of the area is complex, resulting in styles of deformation changing over relatively small spatial scales. Secondly, the local seismicity is relatively sparse and characterized by small-to-moderate earthquakes. As a result, the definition and characterization of the major seismogenic sources and the association with the largest historical earthquakes is still a debated topic. As far as the generation process for the largest tsunamis of the past is concerned, the discussion is even more problematic. For both the 1693 and the 1908 tsunamis, possible earthquake-triggered tsunamigenic landslides have been invoked as necessary and relevant contributors to explain the observed tsunami effects. But the few cases of suitable identified sliding bodies offshore exhibit a very large uncertainty in characterization and dating.

Traditionally, two main methods have been adopted for the quantitative assessment of tsunami hazard, namely the so-called worst-case scenario approach and the probabilistic approach. The latter has got increasing importance, developments and applications especially in the last decade, becoming the most common method used in many national tsunami hazard assessment programs (including the Italian). Nonetheless, two aspects suggest that the worst-case scenario strategy should not be abandoned, but rather has to be considered as a complementary method, especially suitable for geographic areas like eastern Sicily. The first aspect is that the probabilistic approach for landslide-generated tsunamis is still far from a standard setting. Secondly, the largest tsunamigenic events, characterized by very long return periods and by the highest impact, are difficult to be treated in probabilistic terms. The scope of this contribution is to discuss the above points in relation with eastern Sicily, by presenting a critical review of the results published so far and of problems that still remain open.

## High detail fault segmentation: deep insight into the anatomy of the 1983 Borah Peak earthquake rupture zone ( $M_w$ 6.9, Idaho, USA)

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**Keywords:** 1983 Borah Peak earthquake, fault segmentation, surface rupture, rupture zone width, high-resolution topography.

Following the fieldwork along the Lost River Valley (Idaho, USA), we integrate different subsets of both bibliographic and original data to obtain an extremely detailed segmentation of the fault portion that released the 1983 Borah Peak earthquake ( $M_w$  6.9). The earthquake ruptured the topographic surface with a normal-oblique faulting mechanism, activating two SW-dipping segments (*i.e.*, Thousand Springs and Warm Springs) and a branching SSW-dipping fault (*i.e.*, Arentson Gulch Fault), and producing coseismic surface ruptures up to 3 m high. We augment the 1983 earthquake knowledge by investigating and interpreting high-resolution topography and scarps mapping obtained through structure-from-motion. A large dataset of quality selected vertical separation (VS) data, combined with rupture zone width measurements, new fault/slip data, and an analysis of major and minor structural-geometric complexities, highlights a partition of the deformation and a segmentation of the fault up to the detail of four orders (*i.e.*, segments, sections, subsections, sectors), providing new useful details of the Borah Peak earthquake and new constraints for paleoseismic and seismotectonic studies. The fault/slip data show variations along the fault strike that we interpret from the perspective of a kinematic partitioning, which supports segmentation. In 1983, the two main activated segments had completely different rupture behaviors, with important Rupture Zone Widths in the southern portions and with the deformation concentrated along the main fault trace in the northern portions. We show that the distributed ruptures, in addition to being a large percentage of all deformation in terms of a total length of the ruptures (~19.5 km vs 31 km in total for the main ruptures) also accommodate most of the surface deformation (~66%). We also show that 83% of the deformation in terms of length of the surface faulting is located at the hanging wall of the main rupture, while at the footwall it is located the 17%, which becomes 80% and 20% respectively if in terms of VS. We observe a significant correlation between VS, rupture zone width, the position of the rupture (footwall or hanging wall), and fault geometry. From these correlations, we highlight, for example, the control of obliquity and kinematic partitioning in the surface expression of the earthquake propagation. We interpret the coseismic (*i.e.*, 1983) and long-term (*i.e.*, Quaternary) behavior, showing that the two segments activated had similar cumulated behaviors in distributing the deformation among synthetic and antithetic ruptures over time, even if with different geometries. We calculate ratios applying probability density functions, that are consistent with most of the literature but not spatially uniform. These results must be considered in studies on active faulting hazard and suggest caution in establishing rules for land use planning close to active faults capable of rupturing the surface.

## Complex deformation pattern of the October 2016 central Italy earthquakes from DInSAR data

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*Keywords:* coseismic deformation, seismotectonics, DinSAR data, Apennines.

Earthquakes can produce a wide spectrum of surface deformations associated with the main events or between inter-seismic periods. The larger events ( $M_w > 5.5$ ) can trigger deformations such as surface ruptures related to the activation of main active faults and/or other deformations induced by seismic shaking (e.g. landslides, creeping, sink-hole). In the last three decades remote sensing acquisitions (e.g. Synthetic Aperture Radar Interferometry, Lidar differencing, optical imagery and GPS) have reached an impressive detail, useful for detecting high accuracy deformations. In particular, Differential SAR Interferometry (DInSAR), is one of the most powerful and reliable techniques to provide a snapshot of the coseismic deformation generated by earthquakes occurred within complex geological and morphological settings.

In 2016-2017, a long earthquake sequence struck the Apennines in central Italy, producing impressive surface ruptures due to the activation of the SW-dipping extensional M. Vettore fault system (VF). Most of these ruptures are attributed to the 24 August  $M_w$  6.0 and 30 October  $M_w$  6.5 main-shocks and have been investigated by several groups of field geologists soon after the earthquakes. The complex distribution of the observed ruptures reflects the complexity of the geological setting of the epicentral area, where a succession of both carbonate and siliciclastic rocks crops out. Here we present detailed maps of the complex deformation pattern produced by the VF during the October 2016 earthquake in central Italy, derived from ALOS-2 SAR data via DInSAR technique. On these maps, we traced a set of sections to analyse the coseismic vertical displacement, necessary to identify both surface fault ruptures and off-fault deformations, the latter not directly recognizable in the field. At a local scale, we identified a large number of surface ruptures at an unprecedented level of details, improving those previously observed in the field. At a regional scale, the deformation pattern depicts a roll-over anticline, formed at the hangingwall of a main activated fault, with a listric geometry. The rapid detection of deformation patterns from DInSAR technique can provide important constraints on the spatial distribution of the activated fault segments and their interaction. Such information can be crucial for emergency management by civil protection and helpful to drive and support the geological field surveys during the ongoing seismic crisis. These results demonstrate how the proposed approach can be applied for any worldwide earthquake, aimed to provide a wider and faster picture of the surface deformation in areas characterized by complex geology and morphology.

## **Preliminary results from 1D simulation of the seismic response analyses at San Salvador Urban Center**

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*Keywords:* Local Seismic Response, CASTES project, seismic microzonation, El Salvador seismicity, natural hazards.

This note illustrates the preliminary results of an ongoing study on the evaluation of the Local Seismic Response LSR of the Metropolitan Area of San Salvador (MASS), capital of El Salvador.

The city of San Salvador is located between the San Salvador volcano and the Ilopango caldera, in a sub-flat area called “Valle de las Hamacas” (Valley of the Hammocks), due to the intense seismic activity. In this area the affected seismicity is higher than Mw 6 and is due to the presence of a complex interaction between tectonic structures and tectonic, and volcanic phenomena or a combination of the above, all attributable to the subduction of the Cocos plate below of the Caribbean plate. Historically, the main seismic events in the area occurred in 1965 (Mw 6.3), 1986 (Mw 5.5) and finally in January and February 2001 (Mw 7.7 and Mw 6.6, respectively), also frequent seismic swarms occur in the area.

The Balsamo, Cuscatlan and San Salvador formations are present in the MASS, these were originated from the effusive and pyroclastic activity of the volcanoes in the study area. These formations have been deposited since the Pliocene and are intercalated with basaltic and andesitic lavas as well as tephritic material.

As part of the international cooperation project between Italy - El Salvador (AICS), the CASTES project centered on natural hazards in the territory of El Salvador was launched. Therefore, a systematic study of the dynamic characterization of the underground soil deposits and rocks soils and the evaluation of the local seismic response LSR has been undertaken. These studies are based on existing data derived from the seismic-mechanical characterization of the subsoil. Preliminary analyzes of LSR were performed on sites, where seismic station networks with in-hole and on-surface accelerometers are also installed. The sites studied are Hogar del Niño (HDN), Seminary (SEM), Catholic University (UCA), National Geographic Institute (IGN), Geotechnical Investigation Center (CIG), Presidential House (CPR), Hotel Crown Plaza (HCP) and Apopa (AP). In this paper we will discuss the preliminary results of the LSR showing amplifications at the site at long periods. These amplifications may also have been triggered the landslides occurred after the last strong earthquakes of the 2001 seismic sequence.

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## Friction during earthquakes: 25 years of experimental studies

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Keywords: earthquakes, rock friction, faults.

Dynamic fault strength  $\tau$  and its evolution with seismic slip and slip rate are among the most relevant parameters in earthquake mechanics. Given the large slip rate (up to 10 m/s), displacement (up to tens of meters), effective stress (tens of MPa) typical of seismic faulting, thermo-mechanical effects are outstanding: dynamic fault strength is affected by phase changes, extreme grain size reduction, and the production of amorphous and unstable materials in the slipping zone.

In the first earthquake rupture models it was proposed that fault strength decreases inversely with slip rate ( $\tau \sim 1/V$ , Burridge & Knopoff, 1967). Given the lack of determination of dynamic fault strength through seismological methods, elucidating constraints may arise from experimental studies. However, the experimental evidence for the strong dependence of fault friction with slip rate has been lacking for decades. After the preliminary studies of friction in rocks at seismic slip rates (Bridgman, 1936), it has been only with the installation of dedicated machines (Shimamoto & Tsutsumi, 1994) that the extreme deformation conditions achieved during earthquakes have been approached in the laboratory and systematically investigated.

In 1997, Tsutsumi & Shimamoto reported the first data of dynamic fault strength in cohesive rocks at seismic slip rates: this study opened a new era in experimental rock deformation. Several fault dynamic weakening mechanisms first proposed theoretically (i.e., frictional melting lubrication and, more recently, fluid thermo-mechanical pressurization and elasto-hydrodynamic lubrication), were eventually reproduced in the laboratory (e.g., Aretusini et al., 2021). These experiments allowed us also to explore new dynamic fault weakening mechanisms and other will be probably discovered in the future. Nevertheless, the  $\tau \sim 1/V$  relation was systematically observed, independently of the rock composition and presence of fluids (e.g., Di Toro et al., 2011). Nowadays, theoretical thermo-mechanical models, calibrated by experimental measures, enable us to construct constitutive equations for dynamic fault strength which find application into numerical modeling of earthquake ruptures for both natural and human-induced seismicity (Murphy et al., 2018).

Despite these recent advancements, the activation of several proposed dynamic fault weakening mechanisms and their occurrence in natural faults are debated. In this contribution, we will focus on the technical challenges and the main limitations (i.e., poor estimate of the temperature in the slipping zone, lack of *in-situ* observations during rock sliding, determination of the loading conditions that lead to the transition between concurrent dynamic weakening mechanisms, etc.) of the current experimental approach to unravel earthquake-related deformation mechanisms, and their application to the study of earthquakes in nature.

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## The Timpe fault system (Mt. Etna, Sicily): a seismogenic releasing bend along the Alfeo-Etna shear zone

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**Keywords:** mt. Etna, earthquakes and faulting, seismic reflection data, GPS data, geological hazard.

The lower eastern slope of Etna, for a length of about 30 km, is crossed by the Timpe fault system, showing NNW-SSE orientation and resulting from WNW-ESE oriented extension. It is seismically active having given rise to shallow (max 5 km in depth) and low magnitude (max 4-5) earthquakes in the last 150 years. The strongest events caused significant damage if related to the magnitude, even though in very small areas, being characterized by limited mesoseismic areas. Offshore data indicate that the NW-SE trending dextral shear zone of the Alfeo-Etna fault system (Polonia et al., 2016; North Alfeo fault of Gutscher et al., 2016) turns to N-S direction near the Ionian coastline, where the Timpe fault system occurs. Moreover, morpho-structural data show that this latter continues up-slope connecting to the NW-SE trending shear zone constituted by Fiandaca, Linera-Santa Tecla and S. Venerina faults. In turns, they connects the Timpe fault system with the upper slope of the volcano, where the eruptive activity mostly occurs, forming, as a whole, a releasing-bend zone. The NNW-SSE oriented segments show oblique normal-dextral motion, while the NW-SE oriented segments, such as the Fiandaca fault, reactivated on 2018 December 26th, show right-lateral transcurrent movements with associated en-echelon N-S oriented open fractures and, locally, E-W reverse faults. Morpho-structural, geodetic and seismological data, seismic profiles and bathymetric maps suggest that similar geometric and kinematic features characterize the shear zone both on the eastern flank of the volcano and in the Ionian offshore. The Alfeo-Etna fault system probably represents a major kinematic boundary in the western Ionian Sea (Polonia et al., 2016) associated with the relative motion of Africa and Eurasia since it accommodates, by dextral transtensional kinematics, diverging motions in adjacent western Ionian compartments. Along this major tectonic alignment, crustal structures such as releasing bends, pull-apart basins and extensional horsetails occur both offshore and on-land, where they probably represent the pathway for magma uprising from depth (Giacomoni et al., 2012).

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## **Morphotectonic evidences of elusive active faults in a low strain rate region: clues from the eastern Kachchh region (NW India)**

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*Keywords:* Morphotectonics, Bhuj earthquake, active fault.

The Kachchh region (NW India) is a Low Strain Rate region consisting of a pericratonic rift basin with numerous E-W, NE-SW or NW-SE trending thrust faults. In this area, the tectonic forcing magnitude is stronger enough to trigger infrequent significant earthquakes but no stronger enough to overprint the climatic forcing signature. Consequently, the active faults sources of the most significant seismic events are largely poorly known, and their geomorphic signature is subdued. The eastern part of Kachchh experienced a significant number of seismic events such as the 1819-06-16 Allah Bund earthquake (Mw 7.8, also known as the Rann of Kutch earthquake), the 1956-07-21 Anjar earthquake (Mw 6.1), the 2001-01-26 Bhuj earthquake (Mw 7.6) and the 2006 events (Mw 5.0 and 5.6 earthquake occurred along Island Belt Fault and Gedi fault). Even the seismogenic source of the relatively recent Bhuj earthquake, one of the most devastating earthquakes of Low Strain Rate regions, is characterized by almost no morphological signature. The unavailability of outcrop information significantly hampered the detection and parametrization of actively deforming seismogenic faults in this region. In this ongoing work, we propose a multidisciplinary approach to detect active geological structures and their related surface deformation. Our approach mainly consists of quantitative tectonic geomorphology and structural interpretation and modelling. Preliminary results are a morphotectonic evolution model and a 3D fault model of the study area. We use the obtained data to better constraints and parametrize the possible seismogenic source of the 2001-01-26 Bhuj earthquake.

## **The role of inherited structures in the 2016-2017 Central Italy seismic sequence: lessons learned in the framework of the RETRACE-3D project**

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*Keywords:* Central Apennines, 3D geological model, inherited faults, earthquakes.

Soon after the inception of the long seismic sequence that hit Central Italy with the Mw 6.0 of the 24th August and the Mw 6.5 of the 30th October 2016, the need for an accurate 3D geological model defining the structural pattern of the upper crust of Central Apennines arised straightaway. Central Apennines shallow crust is characterized by high structural complexity due to the overprint of subsequent deformational stages, making interpretation of seismotectonics challenging.

The RETRACE-3D project was based on the collaboration between the Italian Civil Protection Department and four of its Competence Centres (i.e., CNR IGAG and IREA, INGV, ISPRA, and scientists of associated universities) to better enlighten the knowledge on the geological setting of the area and explain the relationship between the main fault systems and the observed seismicity.

As a first result, the RETRACE-3D project produced a comprehensive 3D geological model of the region, which has been recently released to the public for further analyses and applications (<http://www.retrace3d.it/contenuti.html>).

The 3D geological model was developed reviewing a wide subsurface dataset made up by seismic profiles and well information acquired for hydrocarbon exploration, interpreted by integrating detailed surface geology and then compared with the 3D hypocentral distribution of the 2009 L'Aquila and 2016–2017 Central Italy seismic sequences. The 3D geological model is constituted by seven lithostratigraphic units bounded by six horizons, which are separated in fault blocks delimited by the major tectonic discontinuities.

The depicted shallow crust architecture pointed to a complex relationship between normal faults mapped at the surface, thrusts developed during the Miocene-Pliocene Apennines orogenesis, and inherited normal faults mostly developed during the Mesozoic extensional phase and the Miocene foreland flexural process. Most of the inherited normal faults, some of them with surface expression and currently active, have been vertically segmented and transported within the thrust sheets, and, at the present, they are interacting with the major thrusts and other inherited structures lying at depth. The 3D model also favoured the comprehension of recent reactivation of such inherited structures during the last seismic sequences, allowing to infer their kinematics inversions with different styles.

This work suggests that fault segmentation, reactivation, capturing, and interaction are relevant processes in fold-and-thrust belt tectonic settings which have experienced subsequent deformational stages, like the Central Apennines. Finally, the recognition of such processes is fundamental to fully understand the seismotectonics of such areas and to give new constraints for a more reliable seismic hazard assessment.

## Morphotectonic, geodetic and seismic analyses to define activity and kinematics of the bounding-faults of the Catanzaro Trough

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**Keywords:** Calabrian arc (Italy), Morphotectonic study, geodetic data analysis, instrumental seismicity, historical seismicity.

The post collisional tectonics of the Calabrian Arc, the arc-shaped sector of the Apennine-Maghrebian chain, caused the development of both longitudinal grabens and transversal structural troughs (Ghisetti et al., 1979). Despite several studies, the origin and evolution of the transversal structures and their role with respect to the longitudinal ones is still unclear. The Catanzaro Trough is a transversal structural depression of the Calabrian Arc, which hosted several strong Italian historical earthquakes, such as the 1609 (Mw 5.8), the 1626 (Mw 6.1), the 1761 (Mw 5.1), the 1821 (Mw 5.1), the 1783 March 28 (Mw 7.0) and likely the 1905 (Mw 7.0) earthquakes (Rovida et al., 2021), whose seismogenic faults are still not well defined. Thus, the study of this area is of considerable interest to clarify: i) the relationships between longitudinal and transversal structures of the Calabrian Arc; ii) the seismotectonics of the region, with implication for the definition of the seismic hazard of the Calabria.

We undertook a multidisciplinary study in the Catanzaro Trough consisting of: i) DEM, Lidar and aerial photos analyses, to map tectonic features; ii) morphometric investigations of fluvial drainage to highlight recent fault activity; iii) structural surveys to define fault kinematics; iv) analysis of seismic and geodetic data to constrain fault activity and kinematics; v) analysis of historical seismicity.

We mapped two main, WNW-ESE trending, basin-bounding fault systems, up to 30 km long: the Lamezia-Catanzaro fault system, to the north of the Catanzaro Trough, and the Maida-Squillace fault system, to the south. Morphometric results indicate that these fault systems are active, since they displace Holocene deposits and are responsible for important perturbations of the present-day drainage network. The analysis of geodetic data, acquired during a span of time of 25 years, allows estimating strike-slip kinematics on the bounding fault systems. In particular, the northern system shows left-lateral component of movement, consistent with instrumental seismicity acquired by the INGV stations in the span of time 1991-2020. In addition, historical earthquakes, occurred in the Catanzaro Trough, confirm the high seismicity of this area and support the hypothesis that the bounding-faults, considering their geometry and length, could be responsible for the historical seismicity.

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## Historical tectonic activity of the Valdobbiadene-Vittorio Veneto thrust (NE Italy)

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*Keywords:* Active and capable fault, eastern Southern Alps, Seismic Microzonation, NE Italy.

In the framework of the Italian Seismic Microzonation Project (Gruppo di lavoro MS, 2008), the Municipalities of Follina, Miane and Cison di Valmarino (Treviso) appointed the University of Udine to carry out a series of paleoseismological trenches on the Valdobbiadene–Vittorio Veneto Thrust, i.e. the eastern segment of the so called Bassano-Valdobbiadene thrust-system. These tectonic features belong to the SW-NE striking, SE-verging Pliocene-Quaternary front of the eastern Southern Alps (ESC) in Veneto and Friuli (NE Italy). At Present, the ESC front shows an active compression estimated in the order of 2-3 mm/year (Serpelloni et al., 2016). Despite the Veneto-Friuli prealpine area was hit by a few strong earthquakes ( $M \geq 6$ ) during the last millennium (Rovida et al., 2021), no significant seismic event affected the area between Bassano and Vittorio Veneto. In order to investigate the recent tectonic activity of the Valdobbiadene-Vittorio Veneto Th., we dug 7 paleoseismological trenches across the morphotectonic anomalies potentially linked to the fault activity. The analysis of the trenches walls pinpointed that: i) all the stratigraphic units (Holocene colluvial and alluvial sediments), with the exception of the ploughed soil, record tectonic deformation; ii) 4 trenches showed a series of E-W striking, medium angle S-verging reverse faults that cut sediments of historical age reaching the topographical surface existing at the time of the seismic event. iii) restoration of the log trenches shows that at least two deformation events affected the area in historical time: based on dating performed by Beta Analytic (AMS method), the age of the last event refers to a period between the XI and XIII centuries AD. The results of our investigations pinpointed that the Valdobbiadene-Vittorio Veneto thrust is an active fault, capable to generate linear morphogenic earthquakes, confirming the hypothesis of Barba et al. (2013) that at Present identify the Bassano-Valdobbiadene Th. as the tectonic feature with the highest seismic potential inside the so called “Montello thrust system”.

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## Database of active faults in Friuli Venezia Giulia: a basic tool for seismic hazard assessment

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*Keywords:* active faults, geodata base, Eastern Southern Alps, Friuli.

The Friuli Venezia Giulia region (FVG) belongs to the easternmost portion of the Southern Alps, where NE-SW trending, S-SE-verging thrusts of the Southalpine Quaternary front interacts with NW-SE-striking right-lateral strike-slip fault-system that characterizes the Italian-Slovenian border area.

Both fault systems are still active as testified by historical and instrumental seismicity (e.g. Rovida et al., 2021). During the last millennium six  $M \geq 6$  earthquakes struck FVG and surrounding regions causing thousands of casualties and widespread damages (1348, Alpi Giulie; 1511, Friuli-Slovenia; 1928, Carnia; 1873, Alpi; 1936, Cansiglio; 1976, Friuli).

Despite the abundance of scientific literature produced after the devastating 1976 Friuli earthquake sequence (see for a review Carulli, 2018), before this project FVG was not equipped with a systematic and homogeneous database of active or potential active faults based on the seismotectonic features.

For this reason, the Geological Service of the Friuli Venezia Giulia Region promoted a research project in collaboration with the University of Trieste, the University of Udine and the National Institute of Oceanography and Experimental Geophysics (OGS) of Trieste in order to create a database of the active faults in FVG. Input data derives from published papers, studies and maps in FVG produced during the past 50 years and based on geological, geophysical, morphotectonic, seismological, paleoseismological data. The database is organized in direct or indirect clues on the location of active or presumably active faults, as well as on their recent activity (e.g. historical, Holocene, post-LGM, pre-LGM, Quaternary and Pre-Quaternary). These clues served to fix major tectonic structures, and to create the map of the active or presumably active faults. When data are available, the structures are characterized by a full set of geometric, kinematic and seismological parameters (e.g., slip rate, recurrence interval). Each parameter is rated for accuracy (e.g. quality index).

We think that this database represents a useful tool to assess both ground shaking scenarios and surface faulting hazard.

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## Seismotectonic analysis of the north-east sector of Calabrian Arc

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*Keywords:* earthquakes, faults, focal mechanisms.

The north-eastern sector of the Calabrian Arc includes the Sila Massif, Sibari plain and part of the Taranto gulf. It is a geologically complex area crossed by a system of active faults since the Middle Pleistocene that makes Calabria one of the regions with the highest seismic hazard in the Mediterranean. These faults are responsible for the morphology of the territory, characterized by high relieves and widespread landslides on a large scale, and they generated strong earthquakes in the past centuries. A first fault system is characterized by normal high-angle faults with a N-S direction which displaces the Sila batolith. Continuing towards the northern part of the area, NW-SE trending normal faults displace the Plio-Quaternary sediments. In the Corigliano-Rossano area, the Rossano Fault is the most important. It is a WNW-ESE neogenic tectonic structure characterized by a left normal-transcurrent kinematics and extending for about 12 Km with an en-èchelon arrangement. It puts the Sila Batolith in contact with Tortonian and Plio-Quaternary sediments and is responsible for the catastrophic earthquake of 1836. In this work we focused on a wide area comprised between 39.2°-39.9° N and 16.2°-17.4° E degrees, making a revision of the recent earthquakes occurred in it. We collected all focal mechanisms available in published papers and analyzing with great detail the seismicity of the last 15 years. During the last century only small to medium size earthquakes occurred in the area, both on land and offshore. The seismic catalog includes hundreds of earthquakes of magnitude  $M < 5$  recorded during the last few decades. This seismicity appears widespread through the area of our study, with depth in the range from 5 km to 40 km below sea level. Swarms of small events ( $M < 4$ ) are quite common in this seismogenetic area. The increased number of seismic stations available during the last decade allowed for detailed analysis of the local earthquakes. We performed a location as accurate as possible of recent earthquakes, including those occurred along the coast and offshore, and computed the focal mechanism of as many events as possible. To estimate the source kinematics of small earthquakes we applied the software FOCMEC (Snoke, 2003), based on the polarity of body waves, and the software HybridMT (Kwiatek et al., 2016), based on the area below the first P wave pulse. We obtained reliable results for more than 30 earthquakes occurred during the last 15 years ( $2.5 \leq M \leq 4.4$ ). Results show a variety of solutions, with predominance of transtensive and reverse kinematics. The location and kinematics of recent earthquakes are in good agreement with the known faults, showing a significant correlation between the computed focal mechanisms and the direction of the tectonic structures. The source analysis of recent seismicity gives interesting insight about the offshore faults.

## **New paleoseismological constraints of late Holocene earthquakes along the Mt. Morrone fault (Sulmona basin, Abruzzi Apennines, Italy)**

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*Keywords:* active faults, paleoseismology, Central Apennines, earthquakes.

One of the major active and seismogenic structures in the Central Apennines is the ca. 23km long Mt. Morrone normal fault system (Abruzzi region, Italy), considered one of the most relevant seismic gaps of the central Apennines both for the elapsed time after the last event (probably 2nd century AD) and the potential and associated maximum expected magnitude (Ceccaroni et al., 2009; Gori et al., 2011). In addition to the few data on its last activation in historical age, the data regarding its Holocene paleo-earthquake history are still very inaccurate. However, the surface expression of the tectonic structure indicates a fault system potentially responsible for large seismic events (Mw 6.5-7); thus, its seismic potential evaluation represents an important task for the earthquake probability assessment of the region. In this frame, we present the results from two paleoseismological trench sites across the fault bounding the Sulmona basin (close to Roccacasale village), affecting late Quaternary deposits. The 15m-long first trench extended from the bedrock fault plane towards the hanging wall block, crossing a near 1.5m-high scarp observed in the field and carved onto slope deposits. The 6m-long second trench was opened at the base of this scarp, 4 meters south of the former site. The stratigraphic sequences exposed on the trench walls are similar at both sites and have been divided into different units. They are composed of Upper Pleistocene stratified alluvial fan deposits locally topped by colluvial bodies and slope scree of Upper Pleistocene - Holocene age. The detailed mapping of the trench walls allowed us to recognize several surface rupture events involving the entire investigated wide fault zone. The most recent evidence of faulting was found at the fault zone affecting slope deposits almost coincident with the above-described scarp, where the faulting event caused the formation of large fissures filled with organic-rich sediments, identified on both trenches. Ages from organic material sampled into the fissures and at different levels in the stratigraphic sequences suggest the occurrence of at least two surface faulting events along this fault within the last 5.4-5.3 kyr BP. Based on the displaced stratigraphic sequence, we estimated a minimum cumulative vertical displacement of 140 cm and 100 cm for the two trenches and a fissure opening up to 60 cm caused by the two events. Based on the D/L vs. moment magnitude scaling law, the amount of the measured slip goes well with the hypothesis of activation of the entire fault system length and seismic 6.5-7 M events. Our results also agree with the ~2.4 kyr recurrence time interval determined from previous paleoseismological investigations on the northern portion of the fault (Galli et al., 2015). Further trace of probably ancient man activities along part of the slope was found emplaced at the south-westernmost sector of the second trench, alongside evidence of its displacement by the latest surface faulting events.

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## **Morphostructural evidence of active tectonics in the Umbria-Marche Apennines, central Italy**

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*Keywords:* active fault, tectonic geomorphology, river long profile, knickpoint, swath profile.

During the last millennium, several strong earthquakes have occurred in the Umbria-Marche Apennines, which makes this area one of the most seismically active of Central Italy. Unfortunately, the lack of reliable instrumental data for strong historical seismic events, and the scarce field evidence of faulting within the Quaternary deposits, make the characterization of active seismogenic structures problematic. Moreover, although these areas have been largely studied, robust and commonly accepted seismic sources are still lacking. In this regard, GIS-aided analysis of both the topography and the river network represents excellent tools to recognise areas with different behaviour in terms of vertical motions, thus allowing to infer location of tectonic structures.

A tectonic-geomorphology study of the Umbria-Marche Apennine has been carried out through a comprehensive large-scale analysis of the topography and the river network, combined with instrumental seismicity and structural geology data. The topography has been analysed by combining elevation map and its derivative (e.g., maximum, mean, minimum and relief map) and swath profile. The latter are 10 km large and runs roughly perpendicular to the main geological structures and the river valleys.

River network has been analysed because rivers rapidly and consistently react to tectonic deformation, with subtle changes in topography recorded by the channels morphology and the river long profile. Moreover, most of the river long profiles show sharp change in channel slope (e.g., knickpoint). These can be either interpreted as due to either lithological or tectonic control. Moreover long profile of some tributaries were also investigated to find indicators of on-going vertical movements.

Topography and river network features have been compared with historical and instrumental seismicity. This comparison suggest that some topography and river network anomalies are placed in areas where the possible epicentre of strong historical earthquakes occur (e.g., the 1741 Fabriano seismic event). In this regard, the identification of active faults and the definition of their dimensional parameters have major implications on the correct assessment of the seismic hazard for large and densely populated village of the Marche Region.

## **Seismic hazard zonation and seismic design codes. A regional perspective.**

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*Keywords:* seismic hazard zonation, Former Yugoslav.

This work presents systematic and comprehensive review of all up-to-date official seismic hazard zonation maps and design codes for the Former Yugoslav (FY) counties. The paper presents the different methodologies for calculation of seismic design forces related to the different design codes and discusses the methodological and outcome differences. Official seismic zoning maps are presented in uniform GIS manner which enables easy visualization and tracking of spatial differences. The implications of different design codes and seismic zoning maps are significant, discussed through variations of seismic design force value on selected particular building samples.

FY countries have a more than 70 years history of implementation of official design codes. The first official building code was enforced in 1948 with Provisional Technical Regulations for Loading of Structures (OGofNRY No. 61/48 of July 17, 1948). The second edition of building code was published in 1964 with Provisional Technical Regulations for Construction in Seismic Regions (OGoSFRY No. 39/64 of September 30, 1964). In 1981, the third and in some FY counties still administrative valid edition was put on force through Technical Regulations for Construction of Buildings in Seismic Regions (OGoSFRY No. 31/81 of June 5, 1981 with Amendments 49/82, 29/83, 21/88 and 52/90). Today, the majority of FY countries have adopted Eurocodes as official design code with single or parallel implementation. Along with the design codes, for this region 13 different seismic zoning maps were in official use up-to-date, 6 of them related to the period 1948-1990 and 7 EC-8 seismic zoning maps.

The concept of design codes as well as seismic zonation has a direct impact on the seismic risk of the built environment. Starting from this point, we believe that it is necessary to review all up-to-date official seismic design codes and seismic zonation maps, building a ground for further research and analysis in domain of seismic risk assessment.

## **S11.**

### **Volcanic Hazard in the terrestrial and marine environment**

*CONVENERS AND CHAIRPERSONS*

*Francesca Bianco (INGV)*

*Giorgio Lacanna (University of Firenze)*

*Marco Viccaro (University of Catania)*

## **A combined analysis of geodetic and geochemistry data during the period January 1994-December 2018**

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*Keywords:* Etna, Gas, GPS, Plumbing system.

We considered the period of activity at Mt. Etna between January 1994 and December 2018, during which events at the volcano showed a great variety of eruptive styles and volcanological characteristics of the activity. These changed from periods of prevalent degassing at the summit craters, such as in the period between 1994-1997, in which essentially recharge of the plumbing system following the flank eruption of 1991-93 has been observed, to periods of strong explosive activity, for example during the flank eruptions of 2001 and 2002-03 or during the lava fountains of 2011-13 and 2015-16 at the New South Est Crater and Voragine, respectively.

We combined geodetic and geochemical data, with order to define the magma storage levels together with the transfer dynamics of magma and gas.

From a geodetic point of view, the observed ground deformation has been analysed and modelled using data collected by the GPS monitoring network of INGV-OE available on Etna. The whole period has been divided into sub-periods showing homogeneous pattern of deformation. The different sub-periods were then modelled in order to obtain the characteristic of the source also in terms of position and depth.

From a geochemical point of view, we have modelled the range of exsolution depths for the main volatile components in the magma (i.e., CO<sub>2</sub>, SO<sub>2</sub>, and H<sub>2</sub>O).

By combining geodetic and geochemical data, we can estimate specific depth ranges, within which preferential magma stopping levels can be found in the plumbing system of Mt. Etna. It is possible to relate these data with different patterns of magma/gas transfer and accumulation, involving phases of either coexistence or decoupling of the liquid and gas phases of the magma itself. The cycles of inflation and deflation individuated have been therefore re-interpreted as a function of degassing and flushing processes occurring at depth, correlating them with the beginning of important cycles of eruptive activity.

The new elaboration of these data cast a new light on how the storage and transfer dynamics of magma (liquid/solid plus gas) can be reconsidered for interpreting the preparing phases of eruptive cycles at the volcano.

## Morphological changes during the 2014 effusive eruption at Stromboli through the integration of subaerial and submarine data

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*Keywords:* effusive eruption, Stromboli, remote sensing, multibeam bathymetry.

This work shows the results of an integrated analysis of multisensor remote sensing data, including SAR amplitude images, lidar, photogrammetric, and bathymetric surveys acquired before and after the August–November 2014 effusive eruption at Stromboli island. This eruption occurred along the steep flank of the 2-km wide Sciara del Fuoco (SdF, hereafter) flank collapse on the NW flank of Stromboli, with multiple lava flows able to reach the sea. Data analysis allows reconstructing the main lava flows dynamics by means of the main morphological changes that occurred along the whole SdF slope. Well-defined and steep-sided submarine ridges were created by lava flows during the early stages of the eruption, when effusion rates were high, favoring the penetration into the sea of lava flows as coherent bodies. Differently, fan-shaped features were emplaced during the declining stage of the eruption or in relation to lava overflows and associated gravel flows, suggesting the prevalence of volcanoclastic breccias with respect to coherent lava flows. Available data also enabled us to roughly estimate the volume of eruptive products emplaced on the Sciara del Fuoco slope during the 2014 eruption, accounting for about  $3.7 \times 10^6 \text{ m}^3$ . Most of the material was emplaced in the subaerial setting (about 80%), differently from what was observed during the previous 2007 eruption at Stromboli, when a large lava submarine delta formed. This discrepancy can be mainly related to the different elevations of the main vents feeding lava flows during the 2007 eruption (around 400 m) and the 2014 eruption (around 650 m). Slope failure processes associated with the 2014 eruption were recognized both in the subaerial and submarine Sciara del Fuoco slope. Particularly, repeated bathymetric surveys show that at least  $6 \times 10^5 \text{ m}^3$  of volcanoclastic material were mobilized in the upper part of the submarine slope close to the main entry point of the 2014 lava flows, representing the largest instability event detected since the 2007 lava delta emplacement.



## **Slipping on the faults of east flank of Mont Etna during December 2018 volcanic unrest. Results and numerical modelling of UNICT\_NET GNSS Network monitoring and Sentinel-1 SAR interferometry**

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*Keywords:* volcano tectonics model, geodetic data analysis, deformation data inversion model.

The short but intense flank eruption developed from SE base crater of Mt. Etna, from 24th till 25th December 2018, was affected by a feeder-dyke which produced a radial deformation along both east and southwest slopes of Mt. Etna Volcano. The intrusion of the dyke has triggered a coseismic and aseismic deformation of Etna shear lineaments causing on 26th December 2018, MW 4.9 earthquake on the Fiandaca Fault, accompanied by the reactivation on 8th January 2019 (ML = 4.1) of the Pernicana Fault. The Geodynamics & GeoMatic Laboratory Working Group, since 2014 has designed and implemented the discrete geodetic network named UNICT-Net, monitoring the framework of shear lineaments affecting the eastern slope of the Etna volcano. The GNSS measurements, improved by literature data, have provided velocity field and displacement, quantifying the aseismic and coseismic deformation of all the main discontinuities of eastern flank of Etna during the 2018 December unrest period. The monitoring of the all lineaments allowed us to observe the deformation of the fault belts during the pre, sin and post- intrusion of the dyke. In particular, we observed that the most of the deformation was released during latter time phase. The strain field was also recorded by Interferometric data (Sentinel-1) with a time series of about one year.

We think that only a part of the stress was accommodated by creep deformation on incipient detachment in the clayey sedimentary substrate. Therefore, the deformation recorded on the surface across all fault segments could be still elastic. In order to improve the deformation monitoring, a permanent GNSS local network is ongoing to be installed between one critical fault segments.

The collected geodetic measurements allowed us to infer the deep geometry and kinematics of two main linked fault segments that we consider as sources of the 26th December 2018 earthquake. The retrieved information, together with analysed structural-geology, tectonic, and rock-physics data, have led to new insights into the volcano tectonics processes.

## Design and implementation of the gas hazard early warning system at Vulcano - Aeolian Islands

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*Keywords:* gas hazard, volcanic degassing, Soil CO<sub>2</sub> flux, volcanic gases, Stable isotopes of CO<sub>2</sub>, diffuse degassing.

Fumaroles at the crater rim and diffuse degassing by soils are distinguished gas sources in the Island of Vulcano. The atmosphere receives volcanic gases, and the concentration of the air CO<sub>2</sub> does change owing to the volcanic degassing. Although the flux and gas composition allowed tracking the fumarolic-solfataric degassing, the emissions of carbon dioxide and hydrogen sulfide caused gas hazards. The isotopic signature allows distinguishing among various CO<sub>2</sub> (i.e., volcanic, air, and exhaust gas derived from the burning of fossil fuel). Therefore, the stable isotopes in CO<sub>2</sub> can help to identify the dominant gas sources at district scale based on mobile surveying, and tracking the volcanic gas hazard at Vulcano. Anomalous soil CO<sub>2</sub> emissions were found near Faraglione settlements in addition to Palizzi, which is far enough the inhabited zone. Significant changes occurred in the CO<sub>2</sub> degassing from these zones, because of the volcanic gas addition. This study shows the results of the survey aimed to identify four sites suitable for deployment of a monitoring system of the gas hazard at Faraglione. The survey was performed in summer 2020 and enabled collecting stable isotope composition measurements of the air CO<sub>2</sub> and CO<sub>2</sub> concentration indoor. The investigation targeted several types of environments including outdoor sites for a direct comparison with the indoor environment. Both the <sup>13</sup>C/<sup>12</sup>C and <sup>18</sup>O/<sup>16</sup>O of the air CO<sub>2</sub> were determined by using a laser-based isotope mass spectrophotometer. A four-wheel car hosted the instrument, enabling isotopic measurements at 1 Hz, and meter-size spatial resolution. During the indoor survey, an infrared spectrophotometer enabled the air CO<sub>2</sub> concentration measurements in the range of 0 - 10% vol. At least four measurements were performed at each site, with 2 minutes sampling frequency. The results allowed evaluating the CO<sub>2</sub> concentration patterns in a time window (i.e., 10 minutes) comparable with the Permissible Exposure Limit (PEL). The results show that indoor air CO<sub>2</sub> concentration was above the current average air CO<sub>2</sub> concentration (415 ppm vol) in several selected sites. Multiple sources of gases contributed to the CO<sub>2</sub> level in the various sites as shown by the isotope signature of the air CO<sub>2</sub>. In a few specific sites, the air CO<sub>2</sub> concentration achieved 6% vol after a few minutes of measurement, owing to the combination of high soil CO<sub>2</sub> emissions and reduced air circulation. This value is higher than the Immediately Dangerous to Life and Health exposure limit (IDLH = 4% vol). The results of this study show that gas hazard mitigation includes several actions in the settled zones of Vulcano Porto. The soil CO<sub>2</sub> flux and the air CO<sub>2</sub> monitoring (i.e., concentration and stable isotope composition) are compelling actions to decrease the volcanic risk.

## Volcanic and non-volcanic fluid emissions: data from EMODnet Geology

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*Keywords:* EMODnet Geology, fluid emission, mud-volcanoes, Italian seas.

The European Marine Observation and Data Network (EMODnet) is a network of organizations supported by the EU's integrated maritime policy. These organizations work together to observe the sea, process the data according to international standards and make that information freely available as interoperable data layers and data products (accessible from [www.emodnet.eu](http://www.emodnet.eu)).

It is subdivided into Lots concerning Bathymetry, Geology, Biology, Chemistry, Physics, Seabed Habitats and Human activities. The Geology Lot ([www.emodnet-geology.eu](http://www.emodnet-geology.eu)) is carried out by a consortium of Geological Surveys and includes data on seafloor sediments grain size, sedimentation rates, Quaternary geology, pre-Quaternary geology and stratigraphy, coastal behaviour, geological events, mineral resources, submerged landscapes.

Datasets available from the "Geological events and probabilities" layers, coordinated by the Geological Survey of Italy – ISPRA, include submarine landslides, earthquakes, volcanic centers, tsunamis, fluid emissions and Quaternary faults. Data gathered by Partners have been conveyed into single Europe-wide shapefiles, complemented by detailed attribute tables.

Mud-volcanoes and fluid emissions of non-volcanic origin have been initially considered separately from volcanic emission, in order to prevent overlaps and confusion, because terms adopted to describe morphological types of mud-volcanoes, especially in the Black Sea, are the same used for magmatic structures. However, during later phases of the project, with increasing resolution and scale of representation, all types of fluid emissions have been gathered together in the same layer.

The major component of volcanic fluid emissions is CO<sub>2</sub>, while the major component of non-volcanic fluid emissions is methane. These latter have been characterized by type, height, region, composition, morphological and activity types, age of activity.

Part of the Italian results has been collected into monographs published by the Geological Survey of Italy, one dedicated to a systematic inventory of submerged volcanic structures (D'Angelo et al., 2019) and one collating contributions on occurrences of fluid emissions (D'Angelo et al., 2020) which is presented in the workshop on September 13<sup>th</sup>.

In the volume dedicated to volcanoes, hydrothermal occurrences are reported wherever information is available. A specific focus is dedicated to mineral deposits associated with fluid emissions in the southern Tyrrhenian Sea and highlights the widespread occurrence of sulfate and sulfide minerals in the surroundings of volcanic structures.

D'Angelo S., Battaglini L. & Fiorentino A. (Eds) (2020) - Inventory of fluid emissions in Italian Seas. Mem. Descr. della Carta Geol. d'It., Dip. per il Serv. Geol. d'It., ISPRA, 105, 110.

D'Angelo S., Fiorentino A., Giordano G., Pensa A., Pinton A. & Vita L. (Eds) (2019) - Atlas of Italian Submarine Volcanic Structures. Mem. Descr. della Carta Geol. d'It., Dip. per il Serv. Geol. d'It., ISPRA, 104, 184.

## Mechanisms of ash production and recycling during low-energy, mid-intensity eruptions at Copahue volcano (Argentina)

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*Keywords:* volcanic ash, infrasound monitoring, eruptive dynamics.

Volcanic ash is the result of extensive magma fragmentation during eruptions. It depends upon a combination of magma properties (rheology, vesicularity, permeability, gas overpressure) and the possible involvement of external fluids during magma ascent. However, fragmentation processes during the ash-dominated, low-to-mid intensity eruptions are still a matter of debate. Combination of morpho-textural data of the erupted ash with geophysical data on the activity can inform about the energy of the activity as well as on the mechanisms of ash production and dispersal. The phase of heavy ash emission occurred during March 2016 at Copahue volcano (Argentina) generated a very low infrasonic amplitude, corresponding to low exit velocity and low magma overpressure. The apparent unbalance between measured geophysical parameters and the intensity of the activity raises a number of questions concerning the links among acoustic pressure, gas overpressure and efficiency of magma fragmentation. Generally, magma-water interaction is supposed to be the main process of magma fragmentation at Copahue. Conversely, our data on ash texture indicate that a process of magma volatile exsolution under low overpressures actively controlled the fragmentation during the investigated eruptive stage. Ash componentry also revealed that a large fraction of deposit consisted of recycled material. Therefore, comparing these results with geophysical information, we interpreted the activity as influenced by a process of energy buffering, operated by the passage of the erupting mixture through a thick layer of granular, ash-bearing crater infilling produced by the ash recycling processes. The importance of this abundant hot, vent-hosted material for the convective stability of the eruptive plume and for the ash dispersal was highlighted, with direct consequences for the assessment of the related hazard and management of eruptive crises,

## State of knowledge about tsunami hazard due to volcanic sources in the Gulf of Naples

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**Keywords:** tsunamis, probabilistic tsunami hazard analysis, pyroclastic density currents, underwater volcanic explosions.

Probabilistic studies of tsunami hazard caused by volcanic activity in the Gulf of Naples were recently published by Paris et al. (2019) and Grezio et al. (2020) presenting hazard curves and maps. Two major tsunamigenic volcanic sources are indicated in the region: 1) underwater volcanic explosions in the submarine part of the Campi Flegrei caldera and 2) pyroclastic density currents from Somma-Vesuvio. The PTHA for the underwater explosions is implemented considering an event tree with different subaqueous eruptions varying in size and locations which generate tsunami waves reaching the coasts of the Gulf of Naples. At the coast sites the probability of exceeding given thresholds of tsunami wave amplitudes are estimated and considered conditional to the occurrence of the subaqueous eruptions. The PTHA for pyroclastic density currents from Somma-Vesuvio consider only medium and large eruptive size classes which are able to reach the coast with the pyroclastic flow thickness necessary to generate sea surface waves. The source probabilities are evaluated by an event tree with the probability of occurrence of eruptions at Somma-Vesuvio, their size, and the capability to generate sea surface waves. These source probabilities are combined with the conditional probabilities that the water surface elevations overcome certain threshold levels at the coastal sites. Other potential sources of volcano-tsunamis in the area exist, such as large landslides in Ischia (Selva et al. 2019). Here, we review the state of knowledge about all potential volcanic sources impacting the Gulf of Naples, as a first step toward the design of a general approach for merging into a unified probabilistic tsunami hazard all potential volcanic sources active in the area.

Paris R., Ulvrova M., Selva J., Brizuela B., Costa A., Grezio A., Lorito S. & Tonini R. (2019) - Probabilistic hazard analysis for tsunamis generated by subaqueous volcanic explosions in the Campi Flegrei caldera, Italy. *Journal of Volcanology and Geothermal Research*, 379, 106-116. <https://doi.org/10.1016/j.jvolgeores.2019.05.010>.

Grezio A., Cinti F.R., Costa A., Faenza L., Perfetti P., Pierdominici S., Pondrelli S., Sandri L., Tierz P., Tonini R. & Selva J. (2020) - Multisource bayesian probabilistic tsunami hazard analysis for the gulf of naples (Italy). *Journal of Geophysical Research: Oceans*, 125(2), p.e2019JC015373. <https://doi.org/10.1029/2019JC015373>.

Selva J., Acocella V., Bisson M., Caliro S., Costa A., Della Seta M., De Martino P., de Vita S., Federico C., Giordano G. & Martino S. (2019) - Multiple natural hazards at volcanic islands: a review for the Ischia volcano (Italy). *Journal of Applied Volcanology*, 8(1), pp.1-43. <https://doi.org/10.1186/s13617-019-0086-4>.

## Assessing long-term tephra fallout hazard from Neapolitan volcanoes on Southern Italy

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**Keywords:** probabilistic volcanic hazard assessment, Southern Italy, FALL3D simulator.

In the past, volcanic hazard assessment was typically based on one or a few, subjectively chosen representative eruptive scenarios, using a specific combination for the values of the parameters related to the eruptive size and intensity to represent a particular eruptive size class. Recently, in modelling tephra load hazard, the natural variability in terms of eruptive size and intensity, vent position and meteorological conditions, has been taken into account (e.g., Sandri et al., 2016; Selva et al., 2018).

Here, we adopted a probabilistic methodology for a novel long-term volcanic hazard analysis which accounts for intrinsic eruptive variability, to quantify tephra load hazard in Southern Italy, from Somma-Vesuvius and Campi Flegrei, on a regional target domain (ca. 600km x 600km, covering Campania, Basilicata, Apulia, Calabria, Sicily) at a 3-km resolution. Numerical simulations were performed by FALL3D model (Folch et al., 2020) in which the values for the eruption parameters are sampled within plausible ranges for given vents and size classes (Small, Medium, Large). Wind profiles have been collected from the ECMWF ERA5 from 1991 to 2020, with a spatial resolution of 0.03° x 0.03°. The results of this tephra fallout hazard scheme provided absolute hazard curves showing how the tephra load exceedance probability varies on the target domain, in 50 years. The results achieved are perfectly similar, in format. To those commonly achieved with the classic approach for probabilistic seismic hazard assessment, and perfectly compatible with fragility analysis in order to compute and rank the associated tephra load risk with the seismic and other natural risks whose hazards are calculated in the same way. Moreover, the proposed method can be extended to larger temporal intervals to quantify the volcanic hazard due to less frequent events that are relevant for the risk quantification on critical infrastructures.

Folch A., Mingari L., Gutierrez N., Hanzich M., Macedonio G. & Costa A. (2020) - FALL3D-8.0: a computational model for atmospheric transport and deposition of particles, aerosols and radionuclides—Part 1: Model physics and numerics. *Geoscientific Model Development*, 13(3), 1431-1458.

Sandri L., Costa A., Selva J., Tonin R., Macedonio G., Folch & Sulpizio R. (2016). -Beyond eruptive scenarios: assessing tephra fallout hazard from Neapolitan volcanoes. *Sci. Rep.*, 6, 24271.

Selva J., Costa A., De Natale G., Di Vito M.A., Isaia R. & Macedonio G. (2018) - Sensitivity test and ensemble hazard assessment for tephra fallout at Campi Flegrei, Italy. *J. Volcanol. Geotherm., Res.*, 351, 1-28.



## Statistical and probabilistic GIS-based approach for the assessing of the hazard by lava flow invasion at Mount Etna volcano (Sicily, Italy)

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Keywords: Etna, lava flows, volcanic hazard, GIS.

Lava flows of Mount Etna are one of the most spectacular scenarios given by the volcano, but at the same time the less known as risk perceived by resident population. Yet the ability of lavas to spread across urban and rural areas, burning and burying buildings, infrastructures and fields, results in high volcanic hazard and risk, mostly because of the high density of inhabitants living around the volcano. At Etna, effusive eruptions occurring from vents and fractures located at low altitude on the volcano flanks are those more prone to produce dangerous scenario because of their proximity with residential areas. The aim of this study is to investigate the lava flow hazard through a GIS-based approach, in which we adopt a statistic and probabilistic methodology. Starting with a literature investigation, we have created a dataset including the last 2500 years of lava flows, which also incorporates significant volcanological data, such as the duration of the eruption (years), vent position, length of the flow (Km) and covered area (Km<sup>2</sup>), erupted magma volume (m<sup>3</sup>) and the eruptive rate (m<sup>3</sup>/s) where available. The GIS software has been used to draw both lava flow distributions and vent locations throughout the Etnean area, in order to obtain a reference map of the flows and their 2D geometries. Another step of this study implies the partitioning the whole selected volcanic area into three domains that has been distinguished on the basis of the altitude: 0-1000 m, 1000-2500 m, and >2500 m a.s.l. In addition, the main domains have been furtherly divided in smaller sectors according to the flank position to finally obtain a total of twelve domains to be characterized. We performed a spatial and temporal analysis of the lava flow invasions for each identified domain. The relationship between areas invaded by lavas in a given sector with respect to the total inspected area allows us to define a threshold for evaluating the hazard associated to lava flow invasion. Based on the obtained parameters, the increasing hazard on the map is shown through a green-to-red colour scale. Moreover, the hazard map is here developed considering different time interval (500 years each) of the Mt. Etna volcanic record. This study may provide a useful tool for assessing the lava flow hazard in potentially dangerous volcanic areas, as it allows a proper and easy assessment of the spatial and temporal distribution of vents and lava flows, which finally will serve to discriminate between spatial domains of different hazard.

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## **Eruptive activity and tsunamigenic landslides at Stromboli volcano (Italy): clues from deposits and future perspectives**

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*Keywords:* tsunamis, tephra, deposit, hazard, Stromboli.

Tsunami deposits are the main evidence of past tsunami wave inundations but are inherently difficult to identify in coastal sediment sequences. The complexity of the process and the multiple interactions with the ground generate a plethora of sedimentary features such as layers of sand and gravel that were typically interpreted in the past as marine transgression events or as storm surges of extraordinary magnitude. Only in the eighties, seminal works highlighted some specific features that allow identification of their origin. Among the variety of triggering mechanisms, landslides occurring on steeply sloped coastal areas, coastal volcanoes or volcanic islands, have been shown to produce devastating tsunamis. Surprisingly, there are only a few clear examples worldwide of the relationship between volcanic activity and landslides.

Based on radiocarbon ages, on stratigraphic, volcanological and archaeological evidence, three well-preserved medieval tsunami deposits were recently discovered along the coast of Stromboli volcano (Aeolian Islands, southern Italy) as shown by Rosi et al. (2019), who suggested that the destructive power of one of these events is also possibly related to a huge marine storm that devastated the port of Naples in 1343 (200 km north of Stromboli). The sedimentological study of the deposits has allowed a detailed characterization of the tsunami sequences intercalated with volcanoclastic deposits and primary tephra and allowed reconstruction of the likely sequence of the volcanic events (Pistolesi et al., 2020). In one case, a violent explosion possibly preceded the tsunami, whereas in the youngest event, the lateral collapse of the volcano flank triggered a tsunami wave that was rapidly followed by sustained explosive magmatic activity and ensuing prolonged ash venting. The hypothesized tsunami-triggering dynamics suggests a close link between volcanic activity and flank collapse, further confirming that the persistent activity at Stromboli makes the volcano particularly susceptible to tsunami generation, confirming the hazard of these phenomena at a regional scale. New stratigraphic trenches carried out in late 2020 also revealed that deeper, older tsunami deposits may be present, suggesting that tsunami and tephra deposits have recorded interactions between past eruptive activity and landslides at Stromboli volcano even further back in the past.

Rosi M., Levi S.T., Pistolesi M., Bertagnini A., Brunelli D., Cannavò V., Di Renzoni A., Ferranti F., Renzulli A. & Yoon D. (2019) - Geoarchaeological evidence of Middle-Age tsunamis at Stromboli and consequences for the tsunami hazard in the southern Tyrrhenian Sea. *Scientific Reports*, 9, 677, <https://doi.org/10.1038/s41598-018-37050-3>.

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## Seismic Tomography of Southern Tyrrhenian by means of teleseismic data

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*Keywords:* seismic tomography, Southern Tyrrhenian.

The topic of my work is a seismic tomography which has as object the investigation of Southern Tyrrhenian. This tomography was obtained by means of inversion of teleseismic data and an iterative computation of them to obtain the so-called residual that is the difference between the observed travel times and these theoretical travel times. The final tridimensional velocity model corresponds to that having the minimum residual. The entire process of operation of a seismic tomography is very relevant in order to investigate subduction zones. This is the case of the Southern Tyrrhenian oceanic back-arc basin. The subducting lithosphere has been mostly consumed along the Tyrrhenian-Apennine system has been consumed with the exception of the Calabrian arc sector. The new seismic tomography, which derived from the inversion of travel times of teleseismic ray paths, travelling in the upper mantle at high depths. The adopted database consists of 1929 teleseisms recorded in period 1990-2012 by 122 southern Italian seismic station directly connected to ISC (International Seismological Centre). The software FMTT was employed for the inversion of these arrival times. I have made 10 horizontal sections of final model from 50 km of depth to 500 km of depth, with an interval of 50 km of depth from each other. I have made 8 vertical sections and 3 transversal sections, choosing as traces the same illustrated by Montuori (2007), for her teleseismic tomography of Southern Tyrrhenian. This work, together with contributions of Chiarabba (2008) and Calò (2012). Summarising, the horizontal sections show an evolution of the high velocity body that represents the Ionian slab. At depth of 250 km, the tomography evidences a sort of “transition” due to the absence of the Southern Tyrrhenian HVA and the occurrence of a low velocity region with maximum of -0.5 km/s scattered between the Aeolian Islands and Calabria. This low velocity region practically splits the Tyrrhenian slab into two parts, in Neapolitan region and in the southern Calabria-northern Sicily region. The presence of this “window slab” could be interpreted as a tear in which unperturbed mantle insert itself.

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Montuori C. (2007) - Teleseismic tomography of the Southern Tyrrhenian subduction zone: new results from seafloor and land recordings. *Journal of Geophysical Research*, 112, B03311.

## **Volcanic hazard monitoring from space using MOUNTS**

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*Keywords:* satellite volcano monitoring Sentinel Deep Learning.

New generations of Earth Observation (EO) satellites, such as the Copernicus Sentinel missions, are now providing freely available imagery with unprecedented spatial and temporal resolutions on a global scale. Importantly, the diversity of sensors on-board the spacecrafts provide the potential for a comprehensive monitoring of volcanic unrest. In particular, the synergetic use of radar (Sentinel-1 SAR), short-wave infrared (Sentinel-2 MSI) and ultraviolet (Sentinel-5P TROPOMI) payloads, are particularly promising for surveillance of surface deformation and topographic changes, emplacement of volcanic deposits, detection of thermal anomalies, and emission of volcanic SO<sub>2</sub>. MOUNTS (Monitoring Unrest from Space, [www.mounts-project.com](http://www.mounts-project.com)) is a monitoring system which intends to demonstrate the potential of such an integrated interdisciplinary approach, where systematic processing and visualization of EO products can support both scientific and operational communities for volcanic risk assessment and management. This presentation will present a number of recent volcanic crisis captured by MOUNTS, and thereby illustrate how a variety of hazards can be detected and monitored from space.

## **The exceptional 2020-2021 paroxysmal activity at Mt. Etna: insights on the pre-eruptive magma dynamics by combining geochemical and geophysical data**

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*Keywords:* Mt. Etna, paroxysmal eruptions, volcanic tremor, olivine crystals, diffusion modeling.

The end of 2020 marked a change in the eruptive behavior of Mt. Etna activity, where the persistent and weak explosive activity at the summit, which lasted for almost two years, shifted to more explosive manifestations. The South East Crater (SEC) is being the theater of a new intense paroxysmal activity, with similar characteristics to those already observed during the 2011-2013 series at the same crater. More than 30 episodes of intense lava fountaining took place since December 2020 until the end of May 2021, with formation of huge ash columns reaching maximum heights up to 10-15 km asl, coupled with emission of rheomorphic lava flows mainly towards the Valle del Bove and southwest of the summit craters. Small PDCs due to collapse of crater portions have also been observed during the most intense episodes. A peculiar feature of this new paroxysmal series is the exceptional cyclicity of the occurrence of lava fountaining. Indeed, starting from February 16, 2021, each episode occurred after 30-50 hours from the previous ones, with further intensification during the series of May 2021 with even 2-3 episodes within 24 hours, suggesting a rather steady rate of gas input in the shallow portions of the plumbing system.

Here, we present preliminary data based on a multidisciplinary approach of investigation that combines petrological and geophysical data. Integration of whole rock compositions, textural and compositional features of olivine crystals with the localization of volcanic tremor sources allow us to decipher the nature of magma dynamics and their spatial and temporal distribution within the plumbing system occurring during pre-to-syn-eruptive stages. Investigations on the physical and chemical conditions of magma involved and kinetics of its movements among the different zones of the plumbing system by modeling the diffusive relaxation of Mg-Fe gradients in olivine crystals are fundamental in understanding the predisposing factors leading to paroxysmal activity, where the abundant production of tephra constitutes a source of inconveniences for local people and for the management of the aviation space. Our study provides significant elements in the evaluation of the volcanic hazard in a densely populated area such as that around the Mt. Etna volcano.

## Dehydration induced by magma ascent velocity and hazard implications for explosive eruptions at Mt. Etna volcano

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*Keywords:* Mt. Etna, explosive eruptions, volatile elements, magma ascent rates.

A new intense eruptive activity characterized the summit of Mt. Etna volcano starting from the 2011 year. Several episodes of violent ash-dominated lava fountaining occurred during the 2011-2013 paroxysmal series at New South East Crater (NSEC) and the 2015-2016 paroxysms at Voragine Crater (VOR), alternating with weakly explosive and/or effusive behavior as observed during 2014 and between 2017 and 2019. We have assessed the initial volatile budget of magmas emitted during three selected eruptions (2013, 2015, and 2018) characterized by variable energy, by quantifying volatile contents in olivine-hosted glass inclusions and embayments. The initial water contents inferred from the studied melt inclusions are high (up to 3.5-4.0 wt.%; Zuccarello et al., 2021) and comparable with those measured in magmas emitted during the highly energetic 2001 and 2002-03 eruptions, although evidences of diffusive volatile loss were recognized. Our study shows that magma dehydration is strongly controlled by the magma ascent rate during the syn-eruptive stages. Estimation of magma ascent rates through-h volatile diffusion modeling along melt-embayments reveals that magma ascended rapidly from 80-120 MPa during lava fountaining episodes that occurred in 2013 and 2015 at NSEC and VOR respectively, corresponding to timescales of 3-14 minutes. Instead, slower ascent rates (with timescales of 22-96 minutes) that caused higher magma dehydration were estimated for the mild-intensity Strombolian activity that occurred during the flank eruption in December 2018.

Insights provided by our study are crucial in the evaluation of hazard at Mt. Etna. Our data support the idea that in the last decade the deep plumbing system of Mt. Etna has been continuously filled by the arrival of water-rich magmas, which translates into a strong potential to produce highly explosive eruptions. Therefore, the almost persistent and weak explosions characterizing the ordinary activity at the summit can shift suddenly to a more explosive behavior depending on magma transfer kinetics from the storage area toward the surface. The huge ejection of tephra into the atmosphere (from 4-5 to 10-15 km asl) constitutes the major source of hazard related to the paroxysmal activity, with particular consequences on the management of aviation safety. Inconveniences also affect the local population due to the abundant fallout of ash and coarse lapilli, as observed in very recent times during the ongoing paroxysmal series started since December 2020 at the South East Crater. Fast kinetics of magma ascent in the case of more powerful events make it challenging to understand the evolution of eruptive phenomena and to assess volcanic hazard at open system and basic volcanoes such as Mt. Etna.

Zuccarello F., Schiavi F. & Viccaro M. (2021) - Magma dehydration controls the energy of recent eruptions at Mt. Etna volcano. *Terra Nova*, 00, 1–7. <https://doi.org/10.1111/ter.12527>.

## **S12.**

### **Landslides in the terrestrial and marine environment**

*CONVENERS AND CHAIRPERSONS*

*Chiara Calligaris (University of Trieste)*

*Maria Teresa Brunetti (CNR - IRPI)*

*Daniele Casalbore (University of Roma - La Sapienza)*

*Mariacristina Prampolini (CNR - ISMAR)*

## **Development of a methodology for the characterization and monitoring of landslides using UAV (Unmanned Aerial Systems) techniques: A case study of a debris flow in Nejapa (El Salvador)**

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*Keywords:* landslides, LIDAR, CASTES project, tomography, El Salvador seismicity, natural hazards.

El Salvador is a territory is formed by young and unconsolidated volcanic materials that are susceptible to rain-induced landslides and seismic-induction landslides.

In El Salvador, LiDAR information has been collected for the entire territory, reaching a resolution per pixel of 1 m<sup>2</sup> which allows to know the geomorphological state of the territory at the national level up to the date of August 28, 2014

The objective of the research was to design a methodology to characterize landslides by implementing cutting-edge technologies such as UAV (Unmanned Aerial Systems), at the same time it aims to produce results that explain the behavior of some landslides related with the type of parent material and the triggering factor. The study site was the landslide occurred in October 29 of 2020 at 23:00 in The Picacho park which is part of the San Salvador volcanic building in the Municipality of Nejapa, Department of San Salvador, El Salvador C. A. The most affected area by the event was the Los Angelitos I and II settlements, it left 7 people died and 105 affected families, the accumulated rain recorded was 57.4 mm the highest of the reference stations according with Environmental Observatory MARN (Ministry of Environment and Natural Resources). The dynamics of slope movements continue to modify the landscape without it being possible to update LiDAR coverage in the short term because of economic issues.

This methodology allowed monitoring the variations at local level of landslides from a DoD (DEM of Difference) method between two Digital Terrain Model, one provided by LiDAR and the other one from UAV Technology photogrammetry technic based, using a structured workflow it was possible to estimates the slipped material volume, deviation, affected area and depth. Information from differential GPS was added to this procedure that helped as control points to improve the precision of the information captured and processed by UAV. With this, a landslide profile was obtained, whose data were compared with those obtained from a non-commercial landslide modelling software (Desviación, área, volume, depth) along the landslide path.

The research was a part of the development of the initiative to study the natural hazards of the Central American region sponsored by the Italian Agency for Development Cooperation through the new CASTES project administered by the University of Palermo, Italy.

Guthrie R. & Befus A. (2021) - DebrisFlow Predictor: an agent-based runout program for shallow landslides. *Natural Hazards and Earth System Sciences*, 21(3).

Williams R. (2012) - DEMs of difference. *Geomorphological Techniques*, 2(3.2).



## Assessment of Badland area variations for two study sites in the Northern Apennines (Italy)

Bosino A.\*<sup>1</sup>, Bettoni M.<sup>1</sup>, Omran A.<sup>1-2</sup>, Bernini A.<sup>1</sup>, Simoncelli L.<sup>1</sup>, Adeniyi O.D.<sup>1</sup> & Maerker M.<sup>1</sup>

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*Keywords:* Badlands, Calanchi, soil erosion, Secchia, Oltrepo Pavese, Northern Apennines.

The aim of the present work is to assess the morpho-climatic conditions that trigger area variations of Badlands, in the lower Secchia Basin, Emilia-Romagna region, (Italy). Furthermore, we compare the results of this study with the area variation trends in other Italian regions. The final purpose is to understand and project the future evolution of the Badlands in the Northern Apennines. Recent studies have highlighted an overall area reduction of the Badlands in the Northern Apennines (e.g., Bosino et al., 2019; Coratza et al., 2021). The general shrinking trend results essentially due to the land use change combined with a slight decrease of precipitation amount during the last decades. In this study, we mapped the Badlands using two sets of orthophotos (1994 and 2018, provided by Geoportale dell'Emilia-Romagna). Consequently, the Badlands were classified from the lithological and morphological point of view following Bosino et al. (2019). In total 213 Badlands were mapped. The Badlands mainly crop out in the soft sedimentary bedrock belonging to the Ligurian and Epiligurian Successions that characterise vast portions of the Northern Apennines. The morphological classification shows that 66% of the Badlands are characterised by a smooth morphology with diffuse vegetation and/or landslide processes (Type B). The photo interpretation has highlighted a general reduction of Badlands areas in the last 25 years passing from 8.6 km<sup>2</sup> to 7.4 km<sup>2</sup>. The shrinking trend comes along with an increase of the dense vegetation inside the Badlands, indicating a reduction of erosive processes. Evaluating the precipitation from 1950 onwards we observed a general decrease in the average annual precipitation from 900 to 650 mm/year (Coratza et al., 2021). Though in the last 25 years the trend seems to be inverted increasing from 600 to 800 mm/year. Monitoring the land use changes from 1994 onwards, we observed a decrease of agricultural fields from 135 km<sup>2</sup> to 102 km<sup>2</sup> and an increase of meadows and forest from 4.7 km<sup>2</sup> to 17 km<sup>2</sup> and from 65 km<sup>2</sup> to 75 km<sup>2</sup>, respectively. Similar trends for precipitation, land use change and Badlands response were observed also by Bosino et al. (2019) in the Oltrepo Pavese area. Furthermore, our study areas are deeply affected by mud flows and shallow landslides that exposes the soft sedimentary bedrock favouring the runoff processes and Badlands development. Our study shows that land use changes are the major driving factor in terms of the stabilization of the Badland areas. The recent trend of increasing precipitation further favours vegetation growth on the condition that stabilization of landslide areas take place.

Bosino A., Omran A. & Maerker M. (2019) - Identification, characterisation and analysis of the Oltrepo Pavese calanchi in the Northern Apennines (Italy). *Geomorphology*, 340, 53-66.

Coratza P. & Parenti C. (2021) - Controlling Factors of Badland Morphological Changes in the Emilia Apennines (Northern Italy). *Water*, 13(4), 539.

## Rainfall thresholds for landslide early warning system in Sardinia

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Keywords: rainfall threshold, landslide, early warning system.

The Research Institute for Geo-Hydrological Protection of the Italian National Research Council (IRPI CNR) has developed in cooperation with Civil Protection of Sardinia Region, a regional early warning system for the possible occurrence of rainfall-induced landslides (SARF Sardinia), which currently compares the national rainfall thresholds with the rainfall measured by national and regional rain gauge networks and with rainfall forecasts provided by COSMO-15 and BOLAM models.

In the framework of the current Collaboration Agreement between the Sardinia Region and IRPI CNR, a catalogue containing meteorological and hydrogeological information related to rainfall-induced landslides in Sardinia has been compiled. The catalogue lists 261 landslides that occurred in the period 2007-2020. The information includes: (i) event identifier; (ii) rainfall data (name and geographic coordinates of the selected rain gauge, duration, rainfall mean intensity, and cumulated rainfall responsible for triggering); (iii) landslide geographic data (region, province, municipality, location affected by the event, geographic coordinates of the landslide, spatial accuracy of the landslide); (iv) landslide type; (v) landslide temporal data (year, month, day, time, temporal accuracy of the landslide); and (vi) source of data/information.

Rainfall series used to reconstruct the landslide triggering conditions include measurements of 186 rain gauges from a Regional Agency network (SASI), 186 additional stations provided by the Environmental Protection Agency of the Region of Sardinia (ARPAS) and the former Hydrological Service (ExSI), and 96 rain gauges from the National Department for Civil Protection network.

Information on rainfall-induced landslides comes from digital and printed newspapers, blogs, technical documents, landslide event reports, and fire fighter reports.

The information in the catalogue is used to define regional rainfall thresholds to be implemented in the SARF Sardinia. Thresholds are defined using the frequentist method, which allows the calculation of cumulated event rainfall–rainfall duration (ED) threshold curves corresponding to different non-exceedance probability levels and including uncertainty in the parameters that define the thresholds.

Currently, the Civil Protection of Sardinia Region is using the implemented system to support decisions in order to issue warning advices.

## The Iterative Pole Density Estimation, a new approach to assessing the stability of rock masses from 3D point clouds

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*Keywords:* data science, algorithms, programming, coding, geomechanics, geostructural surveys, discontinuity, 3D point cloud, 3D data analysis.

Assessment of the stability of rock masses is crucial in the process of risk mitigation. Among the many factors predisposing the Italian territory to geohazards, it has to be mentioned the geological and geomorphological setting, often characterized by karst processes and widespread presence of cavities, of both natural and anthropogenic origin, potentially leading to sinkholes and other instability mechanisms. For these reasons, the study of rock masses has always been of primary importance, as a primary tool to define the susceptibility to geological instability and to safeguard the environment.

To solve the problems related to traditional analyses, in many cases too expensive and difficult to carry out, over the last decade the implementation of new digitalized methods, such as close- and long-range remote sensing techniques, has become essential to quantitatively describe the structural arrangement of rock masses. This necessarily requires robust and reliable methods dedicated to extracting the primitive geometries representing the discontinuities on a rock outcrop. A novel approach, combining observations made in situ with digital results, has been recently proposed (Cardia et al., 2021). This method is able to extract discontinuities clusters in a fully supervised way, thus allowing the user to evaluate every situation by determining specified tolerance angle ranges for both dip/dip direction.

We provide here an ongoing development of the method, based on an algorithm that has been implemented in the software GeoDS. The algorithm takes as input a K value, representing a density threshold, from which it will start searching for coplanar points in a given range of 10° for both dip and dip direction, and a seed range value, that is the number of sample points that the system chooses randomly to evaluate each cluster. The greater this value is set, the more successful is going to be the result; however, this comes with a computation time cost, which extent depends on the computer capability.

This new algorithm, called IPDE (Iterative Pole Density Estimation) is then coupled with a KDE (Kernel Density Estimation), extremely useful to plot the graphic projection, on which the user can choose to manually select points or to evaluate the sets with two different automatic clustering techniques, K-means and Gaussian Mixture. The proposed method aims to improve the evaluation of discontinuities on a rock outcrop in a new and original way.

Cardia S., Palma B. & Parise M. (2021) - Implementation of computation codes in geostructural surveys to evaluate rock mass stability aimed at the protection of cultural heritage. EGU General Assembly 2021, EGU21-343.

## Variability of submarine landslides along the Pontine Islands and intra-slope Palmarola ridge

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*Keywords:* landslide, multibeam bathymetry, seismic, Pontine Islands.

In the last decade, high-resolution multibeam and seismic data collected offshore the Pontine Islands and the intra-slope Palmarola ridge has allowed the identification of widespread landslide-related morphologies, ranging at a different spatial scale and characterized by different post-failure behavior. The continental slope off the Western Pontine island is carved by pervasive disintegrative-like mass-failures due to very high seafloor gradients (8–12°, locally up to 30°) and the presence of regional NW-SE tectonic features active during the Plio-Pleistocene (Chiocci et al. 2003). The Venototene edifice is affected by two groups of landslide scars (Casalbore et al., 2016): the first one affects the edge of the insular shelf between 130 and 260 m water depth, whereas the second group affects the lower slope and surrounding basins down to 1100 m water depth, representing examples of retrogressive failure at the heads of channelized features. Finally, in the Palmarola ridge, two main types of slope failures were identified: disintegrative-like and cohesive-like landslides (Casalbore et al., 2016). The first type is characterized by a complex of small, nested scars affecting the steep and tectonically-controlled eastern flank of the ridge, suggesting a genesis related to retrogressive processes. The cohesive landslides occur along the northern flank of the ridge and are characterized by larger scars, where the material was not completely evacuated, and well-defined debris deposits at their base, with the development of pressure ridges. Tectonic activity and slope gradients represent the main preconditioning factors for the development of instabilities, even if a relationship between pockmarks and landslide scars was also observed.

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## Dating landslide movements at the Carobbio study site, Northern Apennines

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*Keywords:* landslide, dendrogeomorphology, Northern Apennines.

Dating surface movements and define their spatial dynamics through time are the main outcomes of the application of dendrogeomorphological techniques on landslides. With these objectives we reconstructed at the multi-decadal scale the movements of the mainly dormant Carobbio landslide in the Val Parma, focusing our research on a portion at the toe of the landslide slope, along the Parma Torrent, that recently reactivated.

At two study sites located at different altitudes on the recently-reactivated portion of the landslide, 10 trees per site were selected, extracting two cores from each stem of oak trees, in the falling direction (trees were mainly bent towards the valley bottom). By means of the recently-introduced Eccentricity Index (Gattinoni et al., 2019; Leonelli et al., 2021), we could reconstruct the first years of surface movements, dating back to the 1960s. Moreover, it was possible to evidence that before the large displacement occurred in 2010-2011 at the landslide toe along the Parma Torrent (event reconstructed by means of photo interpretation), slope surface movements on the landslide occurred first in the higher portion since 1972. Then, since 1997 the surface movement propagated also to the lower portion of the landslide. Overall, the disturbance signals were therefore recorded in trees at the higher site already approximately 40 yr before the main event and 15 years before at the lower site.

This research underlines the usefulness of the application of the dendrogeomorphological techniques in forested landslide slopes, where other techniques may fail because of the forest cover, of the lack of instrumental and topographic monitoring on the long term and possibly of the lack of high resolution satellite images. Moreover, the retrieved data may be used for spatially define the areas of higher disturbance and for reconstructing the landslide surface dynamics accurately, at the multi-decadal scale (if trees are old enough) with annual resolution.

Gattinoni P., Consonni M., Francani V., Leonelli G. & Lorenzo C. (2019) - Tunnelling in landslide areas connected to deep seated gravitational deformations: An example in Central Alps (northern Italy). *Tunnelling and Underground Space Technology*, 93, 103100. <https://doi.org/10.1016/j.tust.2019.103100>.

Leonelli G., Chelli A., Consonni M., Lorenzo C. & Gattinoni P. (2020) - Multi-decadal dating of surface slope movements in forested DSGSD areas of the European Alps: detecting precipitation triggering factors. *Geografiska Annaler: Series A, Physical Geography* 1-25. <https://doi.org/10.1080/04353676.2020.1813983>.

## **Landslide Susceptibility Mapping by comparing simple GIS-based bivariate methods: the importance of geomorphological dimension beyond the statistics**

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*Keywords:* landslide susceptibility, GIS, geo-statistics, conditioning factors, geomorphometry, slope units.

Landslides susceptibility (LS) is one of the main topic of geomorphological risks studies. Many of that have an exclusively statistical approach with little coherence with the geomorphodynamic models and hard to read susceptibility maps. Even if many different models have been developed, the most common and effective are those based on statistical techniques applied to Slope Units (SUs; Reichenbach et al. 2018). SUs segment terrain in homogenous domains and approximate the morphodynamic response of the slope to the landslides.

This paper presents a LS analysis at the catchment scale based on the comparison of two GIS-based bivariate statistical methods. The Piomba Stream basin, in Central Italy, was selected as test area. It is a strongly anthropized basin whose hillslopes are particularly prone to slope failures due to its geomorphological and geological features. A new simple and reproducible method for delineating the SUs were defined with an original GIS-based terrain segmentation based on hydrography. The LS analysis was performed by comparing two GIS-based statistical methods that use the bivariate statistics based on the Landslide Index approach (Van Westen et al. 1997), originally developed for grid-cell analysis, by adapting the equations. The use of Morphometric Slope Index (MSI) (Buccolini et al. 2012) was tested as predisposing factor for landslides. The entire LS analysis is framed within an experimental design that combines statistical methods, predisposing factors and areal threshold of landslides.

The results have led, on the one hand, to the creation of an up-to-date and detailed geomorphological map of the Piomba stream basin and, on the other hand, to the development on a LSM. They have demonstrated the efficiency of SU segmentation method and the potentiality of the proposed statistical methods in determining the LSM, giving easy to read susceptibility maps. Beyond the purely statistic values, the models obtained adhere to the geomorphological dimension of the terrain and highlight the areas with the greatest propensity to landslides. It emerges that the importance of the predisposing factors for LSM is strictly dependent on characteristics of the study area and that the environmental factors are spatially associated (Pourghasemi and Rahmati 2018).

Buccolini M., Coco L., Cappadonia C. & Rotigliano E. (2012) - Relationships between a new slope morphometric index and calanchi erosion in northern Sicily, Italy. *Geomorphology*, 149-150, 41-48.

Pourghasemi H.R. & Rahmati O. (2018) - Prediction of the landslide susceptibility: Which algorithm, which precision? *Catena*, 162, 177-192.

Reichenbach P., Rossi M., Malamud B.D., Mihir M. & Guzzetti F. (2018) - A review of statistically-based landslide susceptibility models. *Earth-Science Reviews*, 180, 60-91.

Van Westen C.J., Rengers N., Terlien M.T.J., Soeters R. (1997) - Prediction of the occurrence of slope instability phenomena through GIS based hazard zonation. *Geol. Rundsch.*, 86, 404-414.



## Small-scale instability processes affecting volcanic island shelves: the case study of the southern shelf of Porto Santo Island (Madeira Archipelago)

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**Keywords:** Porto Santo Island, volcanic ocean islands, insular shelf, mass-movements.

Shelves surrounding volcanic islands represent only a small portion of the entire submarine edifice that can range a few thousand meters below sea level. Despite their small area, the erosional, depositional, tectonic and volcanic processes affecting the subaerial island leave a significant imprint on the shelf morphology when compared to the slope or the submarine base of the islands (Quartau et al., 2014). Therefore, shelf morphology can be used to improve our knowledge about the island evolution, especially the more recent events. In this study, we use multibeam bathymetry, side scan sonar and seismic reflection data of the southern shelf of Porto Santo Island in Madeira Archipelago to map its seabed morphology and seismic stratigraphy from the nearshore to the shelf edge (~100m b.s.l.), aiming to better understand the evolution of mass-movements affecting the area. In general, the shelf consists of an erosive rocky surface mostly covered by sediments, and locally outcropping on the seafloor. The sedimentary cover on the shelf is highly variable both in thickness and internal architecture, mainly due to different onshore sediment supply and available accommodation space. Two main seismic units have been recognized: the lower one (U1) is interpreted as a transgressive deposit, formed during sea level rise after the Last Glacial Maximum (LGM); the upper one (U2) is interpreted as present-day highstand deposits. Based on the morphological and seismo-stratigraphic differences the study area has been divided in three sectors (Western, Central and Eastern). On the Western and Eastern sectors two sets of submerged erosional terraces have been mapped at different depths (35-45 m, 50-75 m b.s.l.). The overall arcuate shape of the southern shelf edge of Porto Santo Island strongly matches the coastline shape, suggesting the occurrence of an old large-scale landslide event (LS1), prior to the shelf formation (Quartau et al., 2018a). Further incisions on the shelf edge of the Central sector, mapped at and upslope the shelf edge, imply more recent mass-movement processes, LS2 at least older than seismic unit U1 and LS3 formed on the late Holocene, indicating a retrogressive evolution of the instability process. The absence of erosional terraces in the Central sector supports this hypothesis, being probably removed by the LS2 event. The terraces depths and their destruction by the LS2 event suggests that these were formed/modified at least by the MIS 5a-5d stillstands or even by older ones. The estimated volume of the LS2 event (0.6 km<sup>3</sup>) suggests that it might have caused a hazardous tsunami if it failed as a single event. The recent LS3 events, due to their small magnitude were probably not hazardous. In summary, three different mass-movements were defined according to their dimension and position on the shelf: from LS1 to LS3, the scars are increasingly smaller and further upslope. These observations provided a more comprehensive understanding of the recent evolution of Porto Santo insular shelf in terms of mass-movement processes.

Quartau R., Hipólito A., Romagnoli C., Casalbore D., Madeira J., Tempera F., Roque C. & Chiocci F.L. (2014) - The morphology of insular shelves as a key for understanding the geological evolution of volcanic islands: Insights from Terceira Island (Azores). *Geochem. Geophys. Geosyst.*, 15, 1801-1826.

Quartau R., Ramalho R.S., Madeira J., Santos R., Rodrigues A., Roque C., Carrara G. & Brum da Silveira A. (2018a) - Gravitational, erosional and depositional processes on volcanic ocean islands: Insights from the submarine morphology of Madeira archipelago. *Earth Planet. Sci. Lett.*, 482, 288-299.



## Influences of vegetation characters on saturated hydraulic conductivity at catchment scale

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*Keywords:* hydraulic conductivity, root reinforcement, LAI, Vegetation load, Shallow landslides.

Shallow landslides susceptibility assessment usually relies on the parametrization of hydraulic and geotechnical features of soils. Among these, saturated hydraulic conductivity ( $K_s$ ) represents one of the most important soil properties that influences infiltration rates, runoff, groundwater recharge and drainage processes, which makes it of particular concern in the prediction of natural hazards including catastrophic floods and shallow landslides.

On the other hand, it is well known that vegetation may play a positive role towards slope stability and over the last decades many efforts have been done in order to quantify the role of the vegetation towards protection from shallow landsliding (Giadrossich et al., 2017). Basically, there are two main vegetation effects: hydrological (e.g., reduction of the water pore pressure through tree rainfall interception) and mechanical ones (increase of the soil strength due to the presence of roots and increase of the soil shear stress due to the vegetation load).

Soil  $K_s$  is expected to be an important factor that influences plant growth, plant-available water, root system and root biomass and, therefore, this work focuses on the quantitative assessment of the relationship between vegetation characters and hydraulic conductivity.

Study areas affected by shallow landslides were chosen in the Garfagnana and Cardoso basin (Northern Apennines, Italy) and in Mt. Amiata volcano (Southern Tuscany, Italy) where field measurements (about 200) of below-ground vegetation (Root Area Ratio - RAR), above-ground vegetation (Leaf Area Index-LAI and vegetation load) and  $K_s$  were carried out inside, in the neighbour and far outside shallow landslide locations. Acquisition of data within landslides areas was supported by means of a multi-temporal landslide inventory already available for study areas. Below-ground vegetation data were collected in trench profiles, while above-ground vegetation data were acquired using digital relascope and digital cover photography. Measurements of  $K_s$  were carried out by means of both constant and falling head permeameters. Results showed that RAR and soil depth affected  $K_s$ , with a decrease of  $K_s$  as the depth increases and roots decrease. Moreover,  $K_s$  varied for different vegetation types, indicating that shifts in aboveground vegetation features may strongly impact the water dynamics of soil. Above-ground vegetation plays a slight negative role on slope stability. Instead, root reinforcement to soil in terms of a root-related cohesion parameter plays a relevant role for depths involved in shallow landslides.

Giadrossich F., Schwarz M., Cohen D., Cislighi A., Vergani C., Hubble T., Phillips C. & Stokes A. (2017) - Methods to measure the mechanical behavior of tree roots: a review. *Ecological Engineering* 109 part B: 256-271.

## The Taranto Landslide (North Ionian Sea): further morphological and stratigraphical observations and timing of the event by indirect stratigraphic evidences

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*Keywords:* marine landslide, geohazard, landslide morphometric parameters, Ionian Sea, post-slide drape.

In the last decade many studies have focussed on small-scale ( $\leq 1 \text{ km}^3$ ) submarine landslide, since they are more frequent with respect to the larger ones and pose a potential threat for the coastal strip and infrastructures. The potential geohazard of a marine landslide is also related to the timing of the event and therefore is of paramount importance to define, as far as possible, its age. This study deals with the Taranto Landslide, an impressive landslide located 12 km off the coast, in the northeastern sector of the Gulf of Taranto, on the southwest-facing Apulian Continental Slope, with the aim to learn more on its geohazard potential. The dataset used in this study consists of multibeam echo sounder (MBES) data and high resolution Chirp Sonar profiles, dip- and strike-oriented which has served to define the morphometric parameters of the landslide and the thickness of the post slide sediment drape. The failure occurred across a slope gradient ranging between  $3^\circ$  and  $4^\circ$ . The evacuated scar surface extends from 400 m below sea level (mbsl) down to 1000 m deep and is bounded by a well-defined headscarp, up to 75 m high, and by two subparallel lateral scarps 4-6 km away from each other. The total inferred volume of the landslide was derived by the scar dimensions and resulted as being about  $0.3 \text{ km}^3$  (Meo et al., 2018). The slump exhibits a simple geometry, with a single arcuate headscarp and no evidence of retrogressive failure process - such as multiple scars merging or upslope modifications in the form of stepped profiles of the basal evacuation surface - was observed. Besides, the scar surface depicts a sub-parallel profile to the adjacent undisturbed slope, suggesting a single slope-parallel plane of failure along which the sediment and the cohesive blocks glided towards the base of the slope. Therefore a single failure event was inferred to the Taranto landslide.

Based on morphometric measurements and empirical calculations, the kinematics and the tsunamigenic potential of the landslide were evaluated. The outcomes of these analysis revealed that the sediment mass displacement was almost fast, with an inferred peak velocity exceeding 42 m/s, and possibly generated a wave up to 2-3 m high. The age of the landslide was roughly estimated on the base of the post slide drape thickness at 680 mbsl and assuming for this site the same depositional rate calculated by Grauel, 2012 at the coresite GeoB10745, retrieved at -680 mbsl, some 80 km southeastwards. The outcome, although roughly estimated and approximate, gives an age of the Taranto Landslide of about 39 ky, surprisingly coeval to the catastrophic Campanian Ignimbrite (Y5) eruption that impacted large sectors of the Southern Italy.

Meo A., Falco M., Chiocci F.L. & Senatore M.R. (2018) - Kinematics and the tsunamigenic potential of Taranto Landslide (northeastern Ionian Sea): Morphological analysis and modelling. *Landslides and Engineered Slopes. Experience, Theory and Practice*, 173, 1409-1416. <https://doi.org/10.1201/b21520>.

Grauel A.L. (2012) - Calibration of the Clumped Isotope Thermometer to Foraminifera and its Application to High-resolution Climate Reconstruction of the past 2500 yr in the Gulf of Taranto (Eastern Mediterranean Sea). Dissertation No. 20360 ETH Zurich, Switzerland.

## **Civil protection interventions - OCDPC n. 558 of 15.11.2018 - Functional recovery of the Provincial Road No. 20 - Municipality of Castiadas (Sardinia)**

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*Keywords:* flood events, hydrogeological risk, public safety.

On 11 and 12 October 2018, Sardinia was hit by exceptional meteorological events that particularly affected the south-eastern area, in the Sarrabus, and in particular various road infrastructures under the responsibility of the Province of Southern Sardinia. The administrative procedure of the interventions originated from the Resolution of the Council of Ministers of 8 November 2018 which declared a state of national natural disaster. Subsequently, the Ordinance of the Head of the Civil Protection Department n ° 558 of 15 November 2018 was issued, which allowed the first management activities to be started for the planning of the first interventions, the rescue and assistance to the population and the restoration of functionalities of infrastructures affected by adverse phenomena.

The Province, following an inspections carried out by the geologists and the engineers of the Traffic Service, identified 9 intervention areas, particularly affected by flood events. Among these, the one in correspondence with the bridge of the Camisa locality, at Km 23 + 250 of the provincial road n ° 20, was particularly critical.

The procedures for safeguarding public safety and the structure concerned were immediately activated, in conjunction with the Prefecture, the Regional Civil Protection and the municipalities concerned. The temporary interruption of the road was arranged, which at the “Ponte Camisa” was bypassed by the large flow rates of the Rio Corr’e Pruna. The bridge was affected by an exceptional flood which led to the removal of a large part of the road foundation, embankments and escarpments.

In the following days an initial census was made of the serious damage caused, which led to interruptions in the road network, narrowing of the carriageway and considerable risk conditions for public safety.

An estimate of the damage was made and the request for funding was forwarded to the Civil Protection of the Sardinia Region. This estimate concerned the restoration of the work of art and the complete functional recovery and safety of the road artery. The works to be designed also include the verification of the residual functionality of the bridge in the riverbed, the previously installed gabions and the geological and hydraulic study of the erosive phenomena that have occurred.

Following the granting of the requested funding, the restoration work was contracted out, the artifacts were rebuilt, the embankment works and the river bed were strengthened and restructured, able to better withstand any new calamitous events. Appropriate management procedures for the work were therefore provided in the event of an alert of adverse weather conditions.

A first study was therefore carried out aimed at reducing the persistent risk on the area, for which the request for funding for the execution of the mitigation of the danger parameters of the area is being investigated.

## **Civil protection interventions - OCDPC n. 558 of 15.11.2018 - Restoration and functional recovery of Provincial Road No. 97 - Municipalities of Castiadas and Muravera**

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*Keywords:* flood events, hydrogeological risk, public safety.

On 11 and 12 October 2018, Sardinia was hit by exceptional meteorological events that particularly affected the south-eastern area, in the Sarrabus, and in particular various road infrastructures under the responsibility of the Province of Southern Sardinia. The administrative procedure of the interventions originated from the Resolution of the Council of Ministers of 8 November 2018 which declared a state of national natural disaster. Subsequently, the Ordinance of the Head of the Civil Protection Department n° 558 of 15 November 2018 was issued, which allowed the first management activities to be started for the planning of the first interventions, the rescue and assistance to the population and the restoration of functionalities. infrastructures affected by adverse phenomena.

The Province, following an inspection carried out by the geologists and engineers of the Traffic Service, identified 9 intervention areas, particularly affected by flood events.

The situation of the provincial road No. 97 was particularly critical, with seven road sections affected by erosive phenomena and a great state of alteration caused by the considerable outflows that occurred during the calamitous event.

The procedures for safeguarding public safety and the structure concerned were immediately activated, in conjunction with the Prefecture, the Regional Civil Protection and the municipalities concerned. Various roadway narrowings have been prepared due to strong erosion phenomena which have led to a great increase in the danger to road users.

The main hydro-geomorphological erosion phenomena concerned:

- at Km 2 + 600, erosion of the embankment of the road embankment on the progressive right, for about 40 meters and a height of 2.5 meters, failure of the guard rail, anomalous accumulation of materials in the docks;
- at Km 3 + 200, burying of the gutter for a length of 20 meters and of a “road manhole” crossing infrastructure;
- at Km 3 + 850, strong erosion of the escarpment on the right side for about 75 meters in length and for heights ranging from 1 meter to 2.5 meters in height; failure of the guard rails on both sides of the road;
- at Km 4 + 300, erosion of the right escarpment for a length of 16 meters and a depth of 1 meter and consequent erosion of the gutter, partially present also on the left side;
- at Km 4 + 900, erosion of the right escarpment for 23 meters in length and 1 meter depth and consequent erosion of the quay, failure of the guard rail on both sides;
- at Km 5 + 200, erosion of the embankment of the right road embankment for 14 meters in length and 1 meter in height, undermining of the crossing infrastructure and damage to underground services, failure of the guard-rail on the right side, erosion of the left embankment for about 23 meters of length and 1 meter in height, failure of the left guard rail;
- at Km 5 + 400, erosion of the left gutter for 25 meters in length;

An estimate of the damage was then made and the request for funding was forwarded to the Civil Protection of the Sardinia Region. This estimate concerned the restoration of the entire section of provincial road No. 97, and the complete functional recovery and safety of the road artery, both in shape and along the quays and appurtenances. The works to be designed also provide for the verification of the residual functionality of the bridge in the riverbed, the previously installed gabions and the geological and hydraulic study of the erosive phenomena that have occurred.

Following the granting of the requested funding, the restoration work was contracted out, the artifacts were rebuilt, the hydraulic crossing works partially reinforced, able to better withstand any new calamitous events.

A first study was therefore carried out aimed at reducing the risk persisting in the area, for which the request for a loan for the implementation of the intervention to mitigate the hazard parameters of the area is in the preliminary phase.

## **Submarine landslides in the Strait of Sicily: relation with tectonics and climate forcing, contourite deposits and high sedimentation rates, post-LGM sea-level fluctuations**

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*Keywords:* Mediterranean oceanography, Gela Basin, contourite drifts, mass-transport deposits, Middle Pleistocene Transition, Plio-Quaternary, glacio-eustatic variations, sortable silt, bioecozone.

Sediment cores and boreholes, high-resolution sub-bottom and multi-channel seismic reflection profiles allowed to study origin and recurrence of mass-transport deposits (MTDs) emplaced along the eastern slope of the Gela Basin in the Strait of Sicily.

27 stacked MTDs were mapped with volumes between  $< 1 \text{ km}^3$  and  $630 \text{ km}^3$  and related to the different phases of margin evolution since the Pliocene. Sedimentary prograding wedges, fed from the north, developed from the late Pliocene and extended eastward. In the Pleistocene, progradation extended to the southern basin with oblique shelf-edge clinothems (Gauchery et al., 2021a). From the Pliocene to the Middle Pleistocene Transition (MPT, 0.8 Ma), the sediment wedge increased in thickness by 150 m/Myr, afterwards the margin developed an aggradational motif, with sediment rates of 900 m/Myr (Gauchery et al., 2021a). The MPT represented not only a drastic change in margin outbuilding, but also in the volume of submarine landslides, with large tectonic-related MTDs replaced by smaller contourite- and clinothem-related MTDs due to faster bottom currents and increased sedimentation rates.

Contourite deposits formed in the Pliocene but grew significantly during MIS 5 and late MIS 2 (Gauchery et al., 2021a). The presence of erosional surfaces downcutting the contourite deposits favoured the emplacement of the South Gela Basin Slide (SGBS) around 17 kyr cal. BP (Gauchery et al., 2021b). Slope stability analysis indicates that even strong seismic shaking ( $M_w = 6.5$ ) at the offshore continuation of the Scicli-Ragusa fault line, located  $< 10 \text{ km}$  from the SGBS, was insufficient to mobilized it (Zaniboni et al., 2021). SGBS was promoted by high sedimentation rates (up to  $1300 \text{ cm kyr}^{-1}$ ) during the last phase of LGM and early phase of Heinrich Stadial 1 (HS1), driven by a combination of inner-mid shelf sediment input, lateral advection by strong Levantine bottom-current and an abrupt and brief intensification of the surface water speed. During the post-glacial sea-level rise pulses, salinity changes at the interface between surface and intermediate waters lead to enhanced bottom-current erosion and margin instability along the outer shelf and upper slope.

Gauchery T., Rovere M., Pellegrini C., Cattaneo A., Campiani E. & Trincardi F. (2021a) - Factors controlling margin instability during the Plio-Quaternary in the Gela Basin (Strait of Sicily, Mediterranean Sea). *Mar. Petrol. Geol.*, 123, 104767.

Gauchery T., Rovere M., Pellegrini C., Asioli A., Tesi T., Cattaneo A., Trincardi F. (2021b) - Post-LGM multi-proxy sedimentary record of bottom-current variability and downslope sedimentary processes in a contourite drift of the Gela Basin (Strait of Sicily). *Marine Geology*, in press.

Zaniboni F., Pagnoni G., Paparo M.A., Gauchery T., Rovere M., Argnani A., Armigliato A. & Tinti S. (2021) - Tsunamis from Submarine Collapses Along the Eastern Slope of the Gela Basin (Strait of Sicily). *Front. Earth Sci.*, 8, 602171.

## **Integration of geological surveys and remote sensing to assess the sea-cliff stability of a tuff headland in a pocket beach (Ventotene Island, Southern Italy)**

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*Keywords:* Tuff cliff, Terrestrial Laser Scanner, Pocket beach, Sea-cliff erosion, GIS processing, vertical geological map, Ventotene Island.

This study provided a detailed integrated analysis of the erosional processes affecting the volcanoclastic headlands of a pocket beach of a typical Tyrrhenian volcanic island (Ventotene, south Italy)

The stability conditions of the southern Calanave bay sea cliff were evaluated integrating geological field survey, structural analysis of discontinuities and a detailed topographic survey consisting of terrestrial laser scanner and photogrammetry data acquisition and processing. A 3-D model of the sea cliff was developed taking into account the artificial cavities quarried in the tuff cliff structure. The 3D model of the area affected by the recent landslides was created using proximity photogrammetry, the Structure for Motion (SfM) methodology. The fracture network was represented by using high resolution digital models, and projected to realize geostructural vertical mapping of cliff.

The studied tuff cliff is characterized by steep up to overhanging walls, affected by a fracture network which locally isolate blocks in precarious equilibrium. In addition, the pyroclastic deposits that make up the cliff display coarse grained horizons containing blocks of considerable size which, due to the effect of differential erosion, tend to be isolated and are likely to collapse. These beds also result in main sub-horizontal discontinuities that intersect the other fracture planes, often isolating meter-scale blocks. A house is present on the edge of the cliff, connected to a cavity network partially used as a restaurant, thus contributing to the overall hazard scenario. The data acquired in 2012 were more recently compared with further surveys carried out following rock failures occurred in winter 2019-2020 (Ruberti et al., 2020). The detachment planes and failure modalities coincide perfectly with the ones previously assessed. The applied techniques have proven to be important in defining these conditions to address risk mitigation interventions that also take into account the ecological vocation of these coasts.

The study underlines the importance of careful qualitative and quantitative assessment of cliff stability in order to better address coastal planning and shoreline defence strategies for a sustainable use of coastal areas.

Ruberti D., Marino E., Pignalosa A., Romano P. & Vigliotti M. (2020) - Assessment of Tuff Sea Cliff Stability Integrating Geological Surveys and Remote Sensing. Case History from Ventotene Island (Southern Italy). *Remote Sensing*, 12(12), 2006. <https://doi.org/10.3390/rs12122006>.



## Conditions and behaviours influencing people vulnerability to landslides

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*Keywords:* landslide fatalities, loss of life, behaviours, age and gender analysis.

Landslides are frequent and destructive geo-hydrological events that cause harm to people every year worldwide (Petley, 2012). In the 13-year period 2004-2016, Froude & Petley (2018) recorded 55,997 landslide fatalities in 4,862 distinct landslide events at the global scale. Catalogues of landslide fatalities are also available at national and regional level. Nevertheless, a small number of studies have investigated the causes and circumstances that have led to the loss of lives. In Italy, a country where landslides cause significant societal and economic damage every year, a catalogue of landslide events with human consequences is continually updated, and used to determine the individual and the societal risk posed by landslides (Guzzetti 2000; Salvati et al., 2010, 2013; Rossi et al., 2019). Despite the efforts, little is known on the circumstances of landslide fatalities, and their dependence on the age, gender and time of the day. For this purpose, efforts were spent to update the national catalogue (Salvati et al., 2003; 2017) for the 51-year period 1970-2020. We looked specifically to the hour of occurrence grouping them in by day or by night and considering the daytime duration differences during the year. The new version of the catalogue lists 336 fatal landslides that have caused 1099 fatalities. We determined the gender (from the name) of 1,040 landslide fatalities (94.5%), and the age for 1,027 fatalities (93.5%) occurred in Italy in the period 1970 and 2020. Overall, males (587) account for 56.7% and females (453) for 43.3% of the landslide fatalities for which the gender is known in the catalogue. The new collected data allowed determining possible relations between the light condition (day or night), the places (indoor or outdoor), the gender (male, female) and the age (using 4 age categories) of landslide fatalities. We were able to identify the exact times for 948 fatalities (91%) and the exact place indoor or outdoor for 649 fatalities (62.4%). Then, for each fatality, we related the times of occurrence with the place (outdoor and indoor) where people lost their life and with the gender and age. Males lost their life frequently outdoor, mainly inside their vehicles, representing a dangerous death contingency, most of them occurring in daylight. Differently, female landslide fatalities occurred more frequently indoor and in the majority by night revealing for them, the dangerous condition of darkness. Using the national census data and a multinomial distribution we estimated the expected fatalities by gender and age and we compared the results with the observed landslide fatalities distribution. Landslide male fatalities compared to the female ones are significantly higher than those expected by census data, indicating both a diverse propensity towards the risk taking and a different degree of exposure between males and females.



## Apulian landslides in the last decade

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Keywords: landslides, data collection, geodatabase.

Although Apulia is not among the Italian regions most susceptible to landslides, intense weather events have triggered multiple landslides causing considerable damage to infrastructure, property and human health (Martinotti et al., 2017).

In order to collect detailed information about landslide we search for, and critically analysed different information sources: chronicles, technical report and scientific papers, institutional databases, web sources. To validated the information and increase the details in the collected data, cross comparison between the available information sources was performed every time.

Research and collection of detailed information on past geo-hydrological phenomena is a time-consuming activity, but it is, undoubtedly, the starting point for building a reliable database. Apulian landslides presented in this work are included in a geo-hazard database based on LandDefend database structure (Napolitano et al., 2018) freely available on (<http://geomorphology.irpi.cnr.it/tools/land-defend-database-structure>). The Apulian geo-hazard database consider each geo-hydrological phenomena (landslides, floods and sinkholes), triggered by meteorological events, that have caused damage in the 2008-2019 period. The collected data can be used to support qualitative and quantitative hazard and risk assessments, then the evaluation of data accuracy is mandatory. For the purpose, we always compiled specific fields, dedicated to the temporal and geographical accuracy. The same level of attention was adopted to quantitatively measure the accuracy of each information source. To rank the availability, efficiency and accuracy of each information source, three distinct indices were generated. Each index was generated by the combination of three numeric indicators obtained through different evaluation grids.

In the studied period we collected detailed information on 123 landslides occurred in the Apulia region, most affecting Foggia province. The monthly distribution shows that the highest number of landslides is recorded in March and September. With regard to temporal accuracy, we observe that only the week of occurrence is known but, in many cases, we were able to establish the exact hour of occurrence.

Points or polygon were used to geo-localize the landslides. The spatial accuracy of geo-referred landslide phenomena is remarkably high: less than 100 m for 80% of the record.

More that 60% of landslides have caused damage to infrastructure, mainly roads. As concern post-landslide restoration works, costs exceed 3MI€, and range between 3500€ and 38000000€.

Martinotti M.E., Pisano L., Marchesini I., Rossi M., Peruccacci S., Brunetti M. T., Melillo M., Amoruso G., Loiacono P., Vennari C., Vessia G., Trabace M., Parise M. & Guzzetti F. (2017) - Landslides, floods and sinkholes in a karst environment: the 1–6 September 2014 Gargano event, southern Italy. *Nat. Hazards Earth Syst. Sci.*, 17, 467–480.

Napolitano E., Marchesini I., Salvati P., Donnini M., Bianchi C. & Guzzetti F. (2018) - LAND-deFeND—An innovative database structure for landslides and floods and their consequences. *Journal of environmental management*, 207, 203–218.

## UAV photogrammetry-based remote sensing for assessing the short-time evolution of a large earthflow in southern Apennines of Italy

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*Keywords:* earthflow, UAV, landslide mapping, spatio-temporal analysis, GIS analysis.

Unmanned Aerial Vehicle (UAV) technique integrate to geographic information systems (GIS) analysis was widely utilized for studying space-time evolution of several geomorphic processes (Rossi et al., 2018; Borrelli et al., 2019). In this work, the UAV photogrammetry was applied to analyze the geomorphological characteristics and assessment the short-time evolution of a large earthflow (i.e. Vomice landslide), representative of wide sectors of the Apennine chain of Southern Italy. The Vomice landslide is located on the right side of Straface River, north-eastern sector of Calabria region (south Italy). The earthflow exhibits two source zones, a narrow and elongated transport zone, and a lobate accumulation zone (Conforti et al., 2021). It affects an area of  $4.21 \times 10^5 \text{ m}^2$  and display a maximum length of  $1.85 \times 10^3 \text{ m}$ . Spatial and temporal morphological changes of the earthflow were assessed comparing the data of two UAV flights, acquired in the in February 2019 and May 2021, respectively.

The UAV surveys were performed using a Parrot Anafi Drone which is equipped with a 21 Mpixel RGB camera and an on-board GNSS system for the accurate geolocation of the acquired images. For photogrammetric orientation of the UAV images a total of 45 GPS points were used. Thirty of these points were used as GCPs for the orientation process. The remaining points were used as check points (CHKs) to calculate the RMSE of the UAV-3D model.

Orthophoto and shaded relief map of the study area, obtained by UAV-3D model, integrated with field surveys, were used for mapping the detailed geomorphological features of the earthflow area. Spatial and temporal geomorphic changes, quantified by comparing high-resolution UAV DTMs of 2019 and of 2021, showed that several sectors of the earthflow were active and with different rates of topographic change.

Overall, the used approach highlighted the great potentiality of the UAV multi-temporal data to provide detailed information on morphological features and related short-term evolution of landslides.

Borrelli L., Conforti M. & Mercuri M. (2019) - Lidar and UAV system data to analyse recent morphological changes of a small drainage basin. *ISPRS Int. J. Geo-Information*, 8(12), 536.

Conforti M., Mercuri M. & Borrelli L. (2021) - Morphological Changes Detection of a Large Earthflow Using Archived Images, LiDAR-Derived DTM, and UAV-Based Remote Sensing. *Remote Sensing*, 13, 120.

Rossi G., Tanteri L., Tofani V., Vannocci P., Moretti S. & Casagli N. (2018) - Multitemporal UAV surveys for landslide mapping and characterization. *Landslides*, 15, 1045-1052.

## Natural sinkhole hazard in the Friuli Venezia Giulia Region

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*Keywords:* sinkhole, hazard, sinkhole inventory, risk, territorial planning, karst, dissolution.

Sinkholes are natural sub-circular depressions that occur on the surface of the ground and that can represent a risk due to their rapid evolution and their low predictability and also because they can affect urban areas and infrastructures causing important damages. In Italy these phenomena are very common and, since 2002 ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) started a national project aimed at inventory them. The Friuli Venezia Giulia is one of the most sinkhole's prone region and in 2014 the Geological Survey founded specific projects aimed at the identification, characterization and inventory of the natural subsidence sinkhole (Calligaris et al., 2020). Location, type, state of activity, shape and dimension, lithologies involved, data of the event and many other information about each sinkhole populated the Geodatabase. 1284 phenomena were inventoried and distinguished following the Italian classification proposed by Nisio et al. (2004) and the international classification proposed by Gutiérrez et al. (2014) according to which there are 215 bedrock collapse, 77 caprock collapse, 184 cover collapse, 365 cover suffosion and 443 undefined sinkholes. The phenomena are located in different geological contexts: alluvial deposits, Flysch, carbonates and evaporites. The frequency of sinkholes is elevated mainly in the evaporites area due to their high solubility rates. In order to reduce their associated risks (economic, social and human), we imaged an approach applicable to these heterogeneous multitude of phenomena starting from the information included in the Geodatabase. State of activity, classification, lithologies involved and geomorphology are the main parameters used to assign to each phenomenon its hazard.

Calligaris C., Zini L., Nisio S. & Piano C. (2020) - Sinkholes in the Friuli Venezia Giulia region focus on the evaporites.

In: De Maio M. & Tiwari A. Eds., Applied Geology: approaches to future resource management. Springer, 79-90.

Gutiérrez F., Parise M., De Waele J. & Jourde H. (2014) - A review on natural and human-induced geohazards and impacts in karst. Earth-Science Review 138, 61-88.

Nisio S. & Salvati R. (2004) - Fenomeni di sprofondamento catastrofico. Proposta di classificazione applicata alla casistica italiana. Atti Conv. "Stato dell'arte sullo studio dei fenomeni di sinkholes e ruolo delle amministrazioni statali e locali nel governo del territorio Roma 20-21 maggio 2004", 573-584.

## Is it a landslide or a sinkhole?

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*Keywords:* sinkhole, landslide, evaporites, geophysical investigations.

Ground-subsidence phenomena, recognized as sinkholes, linked to the presence of evaporitic bedrock belonging to Permian and Triassic ages, affect several areas of the Friuli Venezia Giulia (FVG) region, NE Italy (Calligaris et al., 2017; Calligaris et al., 2020; Zini et al., 2015 and all the references within). One of the most affected municipality is Ovaro, located in the NW of the region in the Degano Valley, where Permian evaporites are often outcropping or subcropping. Here 93 sinkholes have been identified and, sensu Gutiérrez et al. (2014), subdivided as: 11 bedrock collapses, 9 caprock collapses, 16 cover collapses, 7 cover suffosion sinkholes. The remaining do not have a precise typological attribution due to the lack of data, being most of them not recognizable any more on the field. In such a context, on 11th May 2017, in correspondence of Baus, a hamlet sited N of Ovaro village, along the SR355, a failure shaped as a sinkhole, suddenly occurred. The phenomena affected the road, which had to be closed to the traffic also because a landslide developed on the slope just upstream the formed sinkhole. In order to restore the roadway, important mitigation works were done. The slope was reprofiled, a paved barrier has been placed at the toe of the slope and the road was finally restored. Actually, the houses downstream the road, thanks to the crack-meters placed after the main event, show signs of movement. In order to define the effective nature of the geostatical movement occurred, funded by the Geological Survey of the FVG region, several geophysical investigations have been performed by a team of the Mathematics and Geosciences Department of the University of Trieste. In detail, 3 electrical resistivity tomographies, 3 refractions seismic tomographies and some Ground Penetrating Radar (GPR) profiles have been collected both along the road and in the surround areas. Results confirm a complex situation with strong lateral variations demonstrating that a simple attribution to pure sinkhole or landslide phenomena is not possible, being necessary to support the investigations normally used for sinkhole detection with others typical of landsliding slopes.

Calligaris C., Devoto S. & Zini L. (2017) - Evaporite sinkholes of the Friuli Venezia Giulia Region (NE Italy). *J. Maps*, 13(2), 406-414.

Calligaris C., Zini L., Nisio S. & Piano C. (2020) - Sinkholes in the Friuli Venezia Giulia Region: focus on the evaporites. In: De Maio M. & Tiwari K. (Eds.), *Applied geology: approaches to future resource management*. Springer, 73-90.

Gutiérrez F., Parise M., DeWaele J. & Jourde H. (2014) - A review on natural and human-induced geohazards and impacts in karst. *Earth Sci. Rev.*, 138, 61-88.

Zini L., Calligaris C., Forte E., Petronio L., Zavagno E., Boccali C. & Cucchi F. (2015) - A multidisciplinary approach in sinkhole analysis: the Quinis village case study (NE-Italy). *Eng. Geol.*, 197, 132-144.

## **S13. Floods**

*CONVENERS AND CHAIRPERSONS*

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*Corrado Cencetti (University of Perugia)*

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## Estimation of the unconsolidated material-bedrock shallow interface depth by HVSR and MASW seismic survey for rainfall-runoff modelling

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Keywords: bedrock depth, MASW, HVSR, hydrological modelling.

The shallow unconsolidated material-bedrock interface represents a critical boundary in case of intense rainfall events, leading to more surface ponding and overland flow (Salciarini et al., 2012). The knowledge of more realistic spatial variations of unconsolidated material depth (UMd) would result in better hydrologic simulations, although it requires an intensive field survey which is difficult and expensive.

Since the shallow UM-bedrock interface can reasonably correspond to a seismic impedance contrast in the subsoil, in this study a fast integrated approach, based on passive (Horizontal to Vertical Spectral Ratio, HVSR) and active (Multichannel Analysis of Surface Waves, MASW) seismic surveys (Foti et al., 2011), were carried out in order to evaluate the possible presence and the relevant depth of this limit in the first meters of the subsoil. In particular, HVSR technique was performed to identify the resonance frequencies in the interval 10-50 Hz, while MASW analysis provided the shear wave velocity ( $V_s$ ) estimate.

Another important parameter for the prediction of infiltration and runoff volume from storms, is the saturated hydraulic conductivity ( $K_{sat}$ ), which was measured using a constant head "Aardvark" permeameter. The Green-Ampt equation (Green and Ampt, 1911) was implemented using the FLO-2D model (O'Brien et al., 1993) to simulate infiltration into porous media, where  $K_{sat}$  and UMd are two input data.

Different Mediterranean catchments affected by intense rainfall events (>50 mm/h), causing flood/debris flow, were analyzed. Preliminary results allow to evaluate, applying a rapidly seismic survey methods, how the spatial variations of bedrock depth may influence the hydrological modelling.

Foti S., Parolai S., Albarello D. & Picozzi M. (2011) - Application of surface wave methods for seismic site characterization.

Surv. Geophys., 32(6), 777-825, <https://doi.org/10.1007/s10712-011-9134-2>.

Green W.H. & Ampt G.A. (1911) - Studies on soil physics. J. Agric. Sci. 4, 1-24. <https://doi.org/10.1017/S0021859600001441>.

O'Brien J.S., Julien P.Y. & Fullerton W.T. (1993) - Two-dimensional water flood and mudflow simulation. Journal of Hydraulic Engineering, ASCE, 119(2), 244-259.

Salciarini D., Tamagnini C., Conversini P. & Rapinesi S. (2012) - Spatially distributed rainfall thresholds for the initiation of shallow landslides. Nat Hazards 61, 229-245. <https://doi.org/10.1007/s11069-011-9739-2>.

## Debris floods in mountain streams: Insights from the Vaia Storm (October 2018) in the Tegnas catchment (Dolomites, Italy)

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*Keywords:* Debris flood, mountain stream, high-magnitude flood.

Sediment transfer in mountain streams occurs via processes classified as debris flows, debris floods, and water flows. The analysis of the sediment-water flows occurring during high-magnitude floods is currently a scarcely explored issue. This knowledge gap is particularly striking for the debris floods, a water-driven flood flow with extremely high bedload transport that has been rarely investigated. This study investigates how the transport mechanisms activated in a mountain stream during a high-magnitude flood differ from those triggered during ordinary floods, focusing on the controlling factors and conditions required for debris flood occurrence.

The study area is the Tegnas catchment (drainage area 51 km<sup>2</sup>), a mountain basin of the Dolomites (northeastern Italy) affected in October 2018 by a severe flood (Vaia Storm), whose recurrence interval has been estimated to approximately 200 years. We developed a post-flood survey protocol for distinguishing various flow types based on the features of the flood deposits. The transport processes typifying the stream network during ordinary floods and those occurred during the Vaia Storm were determined through the field survey of the deposits. We observed water flow as a response to ordinary events occurring along the entire Tegnas main stem. During the Vaia Storm, water flow still dominated, although debris floods were documented at several sub-reaches. The unit stream power induced by the Vaia Storm was calculated based on the peak discharge computed at the sub-reach scale using a rainfall-runoff model, and channel widening was determined measuring the pre- and post-Vaia channel width.

The comparison between the high-magnitude and the ordinary flows allowed us to infer the existence of relationships between the transport mechanisms, the hydraulic forcing, and channel dynamics. The upheaval of the ordinary flow types did not occur along the entire stream network: water flows transitioned into debris floods only under unit stream powers exceeding the threshold of 5500 Wm<sup>-2</sup> or downstream of sediment-injection sites. Debris floods occurrence appears to be facilitated by tributaries prone to debris flow and connected to the receiving stream, the injection of fine material into the flows (which can occur as consequence of channel-bank erosion or overbank floodwater re-entering the channel), and channels characterized by high slope and relative narrow section. The occurrence of debris floods caused higher channel widening than that induced by water flows. The complex relationships found between flow types and a range of controlling factors reveal that a detailed characterization that includes field observations is necessary to understand the transport mechanisms that can affect a specific channel site during high-magnitude hydrological events for an accurate and reliable definition of flood hazard at the local (e.g., sub-reach) scale.



## **(In)active channel and floodplain geomorphic response to the autumn 2019 high-magnitude floods in the Orba River (NW Italy)**

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*Keywords:* Floods, geomorphic effectiveness, geomorphological mapping, Orba River.

The Orba River (NW Italy) originates west of Genova and flows northward up to the Bormida River, south of Alessandria, for about 73 km. Its catchment (797 km<sup>2</sup>, elevation ranging between 1287 and 88 m a.s.l.) is prone to severe floods as the uplands convey the closeness to the sea and the relief topographic effect which result in high annual rainfall values and frequent intense rainfall events.

In autumn 2019 the Orba River experienced two high-magnitude floods on 21-22 October and 23-24 November, respectively. Very few data are available from gauging stations: the maximum water level recorded close to the outlet was 7.5 m during the former, and most probably about 5.4 m during the latter.

This contribution illustrates the ground effects triggered by these events along the Orba River floodplain reach (23.8 km), along with the legend developed to map flood-related elements in a typical lowland agricultural landscape with channelized rivers (Mandarino et al., 2021). This study is based on extensive post-flood field surveys, ante- and post-flood GNSS surveys, and aerial photographs interpretation.

The former flood resulted in in-channel sediment mobilization, bank retreats, and channelization structures collapses. However, no relevant active-channel planform variations substantially occurred despite the very high magnitude of this event. This behaviour was supposed to be related to the progressive incision and channelization dated back to the twentieth century that restricted the river potential for adjustment. Over the floodplain, erosional and depositional processes shaped new and existing landforms and deposits resulting in severe damages to cultivated fields, transport infrastructures, and buildings. Alluvial gullies (Brooks et al., 2009), overbank deposits, crevasse splays, and surficial erosion evidences were mapped, and the interference of anthropogenic elements on flood propagation, and thus on triggering morphogenetic processes, was highlighted. The latter and lower-magnitude flood exacerbated the aforementioned ground effects overall over the floodplain.

The outcomes constitute an essential basis for hydro-geomorphic hazards assessment and mapping, and thus for river management and land use planning (Hooke, 2015), and provide insights for further research on geomorphic effectiveness of high-magnitude floods.

Brooks A.P. Shellberg J.G., Knight J. & Spencer J. (2009) - Alluvial gully erosion: An example from the Mitchell fluvial megafan, Queensland, Australia. *Earth Surface Processes and Landforms*, 34(14), 1951-1969.

Hooke J.M. (2015) - Variations in flood magnitude-effect relations and the implications for flood risk assessment and river management. *Geomorphology*, 251, 91-107.

Mandarino A., Luino F. & Faccini F. (2021) - Flood-induced ground effects and flood-water dynamics for hydro-geomorphic hazard assessment: the 21–22 October 2019 extreme flood along the lower Orba River (Alessandria, NW Italy). *Journal of Maps*, 1-16.

## Geomorphic effects of large floods: some examples from Italian rivers

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*Keywords:* bank erosion, channel widening, channel planform changes, bed level changes, flood response, channel evolutionary trajectory.

An increasing number of heavy precipitation events causing flash floods, debris flows and other types of landslides, as well as severe morphological effects on changes have affected Italy and Europe over the last years (Tarolli et al., 2012). Italian territory is particularly prone to these types of phenomena, due to a combination of distinctive topographic and meteorological characteristics (Rinaldi et al., 2016).

Extreme events induce physical impacts on rivers and valley bottoms, consisting in channel widening (due to bank erosion and overbank deposition), changes in bed level, avulsions, huge amount of sediment transport, as well as recruitment of large wood. On overall, channel widening is the dominant geomorphic effect observed in many rivers. If on one hand channel widening represents an essential process to sustain channel morphology and fluvial ecosystems, on the other hand, in highly populated fluvial corridors, it can result in the loss of agricultural land and damages to buildings and infrastructures; thus, it should be considered a natural hazard and a major management problem.

Interests in geomorphic effects of large floods have been intensively increasing over the recent decades. At Italian level, several case study papers were published, and new integrated approaches were proposed (Rinaldi et al., 2016). Even, the Italian Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) have proposed a method (the Event Dynamics Classification - EDC, Rinaldi et al., 2015) which provides tools to predict the geomorphic flood hazards, and supports the definition of morphological river corridors, meant to be complementary to inundation maps determined by “classical” hydraulic modelling.

In light of this, an overview of recent studies on flood events at Italian level is presented, with the aims to highlight similar trends in channels changes induced by large floods and to assess the relative role of the different hydrological and morphological factors controlling the flood geomorphic effectiveness.

*Acknowledgments:* Funded by the Autonomous Province of Bolzano (Project: CoupEvent, Hillslope - Channel coupling during extreme events in South Tyrol).

Tarolli P., Borga M., Morin E., Delrieu G. (2012) - Analysis of flash flood regimes in the north-western and south-eastern Mediterranean regions. *Natural Hazards and Earth System Sciences*, 12, 1255-1265.

Rinaldi M., Surian N., Comiti F., Bussettini M. (2015) - A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. *Geomorphology*, 251, 122-136.

Rinaldi M., Amponsah W., Benvenuti M., Borga M., Comiti F., Lucia A., Marchi L., Nardi L., Righini M., Surian N. (2016) - An integrated approach for investigating geomorphic response to extreme events: methodological framework and application to the October 2011 flood in the Magra River catchment, Italy. *Earth Surf. Process. Landf.*, 41, 835-846.

## Catchment response to different severity storm floods: channel variations and hillslope sediment coupling dynamics

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*Keywords:* basin-scale analysis, flood magnitude, sediment connectivity, coupled debris flow, channel widening and bed level changes, DEM of difference (DoD).

Several heavy precipitation events causing flash floods, debris flows, landslides, and morphological channel changes have occurred in Europe over the last years. In mountain environments, mass movements along the hillslopes are important sources of sediment supply to the rivers, and may enhance the geomorphic effects of floods. The Stolla creek (catchment area: 40 km<sup>2</sup>) is a confined/partly confined channel of the Dolomites (Easter Italian Alps), that was affected by an extreme flood in August 2017, and by a moderate flood in August 2020.

The geomorphic effects of the two floods were investigated in the main channel and along the hillslopes with the aims: to compare the channel changes induced by the two events; to assess the impacts of the lateral sediment connectivity to the channel response.

A multi-methodical approach was applied, including radar rainfall estimation, rainfall-runoff modeling, field surveys, remote sensing, geomorphological and statistical analysis. Hillslope and channel processes were mapped by comparing multitemporal orthophotos and Digital Terrain Models. Debris-flow connectivity to the main channel was derived by combining field evidence and geomorphometric analysis. The 2017 flood was caused by rainfall with a short duration (6 hrs) and a rain rate exceeding 45 mm in one hour. More than 600 debris flows were triggered along the hillslopes, among which 23 were connected to the Stolla. Important discontinuities for the sediment flux were represented by the floodplains. The Stolla channel experienced channel widening occurred through bank erosion, and overbank depositions. With ratio (ratio between the channel width after and before the flood) was between 1.3 and 4.9. Widening was accompanied by channel bed aggradation up to 1.2 m or incision up to -2.2 m. Widening through bank erosion was more common in narrower reaches, affected by higher flood power, and presenting higher connectivity with debris flows. Although 294,000 m<sup>3</sup> of sediments were eroded in the connected debris flows and 12,380 m<sup>3</sup> were transferred to channel from toe erosion processes, limited volumes of sediments (< 1000 m<sup>3</sup>) were exported to the catchment outlet.

The 2020 flood event was characterized by a lower rain rate (max 17 mm h<sup>-1</sup>) and a long duration (48 hrs) and did not trigger debris flows. The moderate magnitude of the flood peak did not lead to channel widening, but only bed incision (up to -1.4 m) in the reaches where the 2017 event had caused channel-bed aggradation occurred.

The main results of this study are summarized below:

- different rainfall intensities and durations controlled both channel changes and sediment transport effectiveness;
- sediment supply from hillslopes played a relevant impact in channel adjustments;
- the structural connectivity strongly influenced the sediment cascade.

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## Historical floods in Benevento (southern Italy): a documentary approach

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*Keywords:* Hydrological extremes, channel adjustment, fluvial hazard, Calore River.

The results of the long-term analysis of floods occurred along the middle Calore River and its main tributaries (Tammaro, Sabato) in the surroundings of the town of Benevento since 1501 (Mazzacca, 1992; Zazo, 1986; Guerriero et al., 2018) are here presented. Special focus was paid on both the spatial distribution of the overflowed areas and the frequency of flood events. To this aim, a comparison of some selected historical extreme floods was carried out by means of documents and maps analysis. Such fonts allowed reconstructing the flooded areas and assessing the channel changes (Magliulo et al., 2013). The oldest events were often reconstructed on the basis of both administrative reports aimed at determining the compensatory damages and/or new projects for the repair of damaged infrastructures (Mazzacca, 1992).

At last, examples about the historical aspects of flood protection in Benevento are presented in order to improve the understanding of risk analysis and therefore risk management. Flood walls, aimed at protecting the present urbanized alluvial plain from floods, were built along the riverbanks in the XX century. Other similar riverbank protection structures were built since VI and VII centuries in those stretches which were frequently overflowed (i.e., in the mills area). However, the estimation of the floods, and therefore the possibility of damages, should consider other variables, such as the land use and anthropic infrastructures (Magliulo & Valente, 2020).

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## **Image processing to monitoring morphological changes in river systems: an application to River Paglia (River Tiber basin, central Italy)**

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*Keywords:* fluvial dynamics, multispectral analysis, GIS.

Remote sensing is an important tool for risk mitigation and management of natural disasters (Van Westen, 2000). Multispectral images are used in various fields for rapid feature identification over large areas; furthermore, the short time interval in image capturing allows for the temporal analysis and monitoring of feature variations (Sonka et al., 2014). Image processing and classification techniques can also provide interesting applications in fluvial geomorphology, for outlining morpho-sedimentary features (bars, channels, banks and floodplain) at various temporal stages, in order to monitor the evolution of river systems.

Monitoring is essential for understanding the dynamics of river systems, particularly in Italian streams that experience rapid channel changes and human disturbance leading to an increase in the risk of flooding in anthropic areas.

We show the results of a study aimed at evaluating the planimetric changes which affected the riverbed of the River Paglia (one of the main tributaries of the River Tiber, in central Italy), as a consequence of the flooding event of November 2012. It shows critical characteristics from the morpho-sedimentary dynamic point of view. The riverbed is in a state of sediment-limited non-equilibrium: it is characterized by an intensely active vertical erosion, which led the thalweg to cut through unconsolidated alluvial sediments up and over the bedrock, formed by overconsolidated marine clays. Over time, but especially in the last 50 years, the morphology of the river has changed drastically: the main channel has entrenched and its riverbed has shrunk considerably, leaving most of the bars, which were non-vegetated and active in the past, but now are inactive and covered with dense vegetation of tall trees (abandoned riverbed). Thus, the river has gradually become a “single-channel with low-sinuosity” channel type.

An automatic and/or semi-automatic procedure was developed, in order to study the riverbed changes. The procedure starts from the classical photogrammetric techniques, based on multispectral classification, and goes on with post processing operations of pixel aggregation and shadow treatment. The classification also uses the elevation information provided by a Digital Surface Model produced by photogrammetry. The procedure allows for both the identification and classification of the fluvial features in a post flooding condition. Application of the procedure over time permits the evolution of the fluvial dynamics to be monitored in an accurate and inexpensive way, particularly for flood event conditions which lead to major changes in the dynamics of riverbeds.

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**S14.**  
**Geo-pollutants**

*CONVENERS AND CHAIRPERSONS*

*Barbara Nisi (CNR – IGG)*

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## **A new protocol to evaluate asbestos content in contaminated groundwater samples from Naturally Occurring Asbestos (NOA) rich areas**

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*Keywords:* asbestos, groundwater, NOA rocks, analyses protocol, electron microscopy.

Asbestos is a group of inorganic geo-pollutant which can easily migrate in the environment. Asbestos may be released from solid sources (rocks, soils, asbestos containing materials buried in illegal dumps) by weathering, erosion or anthropogenic activities. Fibres could then follow different paths, such as dispersion in air with subsequent redeposition in water or soil, or directly migrate in surface waters or groundwater.

In NW and Central Alps, where Naturally Occurring Asbestos (NOA) rocks are widespread, possible diffusion of asbestos in water has been recently considered as a consequence of interactions with NOA rocks, such as meta ophiolites. Migration through water (particularly groundwater) far away from the pollution source, which was considered negligible in the past, has gained new attention since a recent laboratory study based on columns has highlighted asbestos mobility through porous media under particular conditions (Mohanty et al., 2021); this suggest that the same could happen in the environment.

Consequently, concerning groundwater management in NOA rich areas, asbestos pollution could represent an environmental problem and even constitute a risk for human health. In fact, it could become airborne after water vaporization, particularly dangerous indoor because it increases the possibility of disease outbreaks related to airborne asbestos respiration (e.g. IARC, 2012). On the contrary, potential noxiousness of waterborne asbestos ingestion has not been defined yet (WHO, 2020); therefore, only US-EPA set a Maximum Contaminant Level (MCL) of 7 MFL (millions of fibres per Litre) in drinking water, considering fibres longer than 10 µm and based on TEM analyses. Italian regulations foresee SEM-EDS analyses for asbestos evaluation in water samples but don't set a MCL. No limits are set worldwide on non-drinking waters.

Knowing this background, it's fundamental to define reliable protocols shared by the whole scientific community for sampling and analysis of water, in particular groundwater, with special attention to asbestos occurrence evaluation. Therefore, based on groundwater samples coming from a recent campaign settled in Piedmont (NW Italy), important developments on this topic will be presented. Several observations on the methodology to evaluate asbestos content in water involving both SEM and TEM analyses will be shared, in an attempt to define a reliable procedure suitable for waterborne asbestos evaluation in potentially usable waters.

IARC-International Agency for Research on Cancer (2012) - Monograph on the Evaluation of Carcinogenic Risks to Humans: Arsenic, Metals, Fibres, and Dusts.

Mohanty S.K., Salamatipour A. & Willenbring J.K. (2021) - Mobility of asbestos fibers below ground is enhanced by dissolved organic matter from soil amendments. *Journal of Hazardous Materials Letters*, 2.

WHO-World Health Organization (2020) - Asbestos in Drinking-water. DRAFT Background document for the WHO GDWQ, December 2020, version for public review.



## Chemistry of atmospheric depositions over two polluted industrial areas of Sicily (Italy)

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Keywords: rainwater, atmospheric deposition, trace elements.

Dry and wet depositions provide the pathways through which particles and gases emitted into the atmosphere return to the Earth's surface. Bulk deposition is defined as the sum of dry and wet deposition, which is characterized by water-soluble and insoluble chemical species. Recent studies (e.g. Castillo et al., 2017) showed that most of the atmospheric deposition in Europe occurs in the wet form, but in southern European regions the role of dry contribution can be as significant as that of wet deposition. In the framework of the multidisciplinary project "CISAS" (Centro Internazionale di Studi Avanzati su Ambiente, ecosistema e Salute umana), bulk depositions were monthly sampled over two polluted industrial areas of Sicily (Milazzo and Priolo), through a network of 12 bulk collectors, from June 2018 to July 2019. In that period, 137 samples were collected and subdivided into 4 aliquots for different analytical determinations: (i) unfiltered aliquots for the total alkalinity; (ii) filtered aliquots (0.45 µm filters) for major anions by ionic chromatography (IC); (iii) filtered and acidified (with Ultrapure HNO<sub>3</sub>) for the analysis of major cations and a large suite of trace elements, respectively by ICP-OES and ICP-MS; (iv) unfiltered and acidified aliquots for the same suite of trace elements, to evaluate the contribution of less-soluble species. The filtration of the rain samples allows the separation of the water-soluble fraction from the particulate fraction (> 0.45 µm), which the filter retains. The comparison between filtered and unfiltered aliquots allowed to highlight the different geochemical mobility of the trace elements, and their distribution among the two fractions. The unfiltered aliquots, therefore, represent the less-soluble species found in the particulate under typical rainwater pH values (4 – 8), that becomes soluble due to the acidification of the samples (pH < 1).

Results showed that the less-soluble fraction represents a significant part of the bulk deposition for several trace metals, especially during dry-dominated periods which are characterized by a long-range transport of geogenic particles (e.g. desert dust). In particular, Al, B, Ba, Fe, Li, Sr, and Ti showed significant enrichment if the less-soluble fraction is included. Similar enrichments are noteworthy also for As, Cr, Co, Cu, Ni, Pb, Se, Tl, Te and V which can be attributed to the local industrial atmospheric pollution, as well as to Mt. Etna that is a permanent source of several volcanogenic elements (Brugnone et al., 2020).

Brugnone F., D'Alessandro W., Calabrese S., Li Vigni L., Bellomo S., Brusca L., Prano V., Saiano F. & Parello F. (2020) - A Christmas gift: Signature of the 24th December 2018 eruption of Mt. Etna on the chemical composition of bulk deposition in eastern Sicily. *Italian Journal of Geosciences*, 139(3), 341-358.

## **First continuous and real-time measurements of gaseous elemental mercury (GEM) from an UAV: the case study of Abbadia San Salvatore ex-mining area**

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*Keywords:* GEM, gaseous mercury, unmanned aerial vehicle, heavy-lift octocopter, 3D spatial distribution.

Air quality assessment and pollutants behaviour are key issues of global environmental policies. Research and monitoring programs have to carry out inventory and control of pollutants sources and enforce the knowledge on how mechanisms of pollutants dispersion in the atmosphere work by also testing new procedures and measurement methods. Gaseous elemental mercury (GEM) is a toxic and noxious species for humans and natural environment at local and global scale, being released from natural and anthropic sources. In particular, mining and smelting processes of cinnabar ore in Hg-mineralized areas are known to affect the surrounding environments where past and present mercury industrial activities operated.

In this work, we present, to the best of our knowledge, the first real attempt to directly and continuously measure GEM by means of a Lumex RA-915M, designed for real-time detection and monitoring of mercury vapour, mounted on an Unmanned Aerial Vehicle (UAV, namely a heavy-lift octocopter), inside and outside the former Hg-mining area of Abbadia San Salvatore (Mt. Amiata, Italy), known as a GEM source. We tested the effectiveness of the UAV-Lumex combination at different heights in selected sites pertaining to both mining facilities and surrounding urban and inhabited zones, shedding light on the GEM spatial distribution and concentration variability around the sites. The great sensitivity of Lumex and the optimal versatility and manoeuvrability of the octocopter in both horizontal and vertical dimensions allowed to depict the GEM distribution in the atmosphere up to a height of 50 m. Additionally, the acquisition system was optimized by: i) the correct synchronization of Lumex and UAV GPS data by means of a stand-alone GPS previously synchronized with Lumex at ground; ii) the use of a vertical sampling (1.20 m high) tube connected to the Lumex inlet to overcome the strong airflows generated by the rotors and to avoid any air turbulence able to affect the GEM measurements; iii) the use of batteries for power supply, avoiding the release of exhaust gases; iv) the UAV ability to land in small spaces and stop at desired altitudes.

The resulting dot-map graphical representations, providing a realistic 3D picture of GEM vertical profiling during the flights in near real-time, were useful to verify whether the guideline concentrations indicated by competent authorities were exceeded in order to undertake appropriate actions to mitigate the possible risk for the local community. The results showed that the GEM concentrations in the urban area, located a few hundred meters from the mining structures, and close to already reclaimed areas remained at relatively low values and did not change substantially both horizontally and vertically. Contrarily, GEM contents showed significant variations and the maximum values in close proximity to the facilities containing the old furnaces, concordantly with a GEM increase with either decreasing heights or downwind.

## **Risk assessment to atmospheric mercury pollution in workplace indoor air: the case of *Central Italian Herbarium* (Museum of Natural History of Florence, Italy)**

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**Keywords:** gaseous mercury, risk assessment, workplace air.

Indoor air quality is a fundamental goal to ensure health and safety in workplace, especially in those environments affected by heavy metals pollution. This is the case of botanical sections of Natural History Museums (i.e., herbaria) where the past use of mercury dichloride (HgCl<sub>2</sub>) for the conservation of the plant sample currently produces high levels of gaseous elemental mercury (GEM).

In this work we quantify the hazard quotient (*HQ*) to GEM exposure for the workers of the *Central Italian Herbarium* (Museum of Natural History of Florence, Italy) employing the Environmental Protection Agency of United States (US EPA) model for inhalation risk. The *HQ* quantifies the potential for non-carcinogenic toxicity occurring to a chronic exposure and it is expressed as the ratio between the estimated indoor air pollutant concentration ( $EC_{air}$ ) and the reference concentration (RfC, i.e., the threshold value that is likely to be without an appreciable risk for human health). Values of  $HQ > 1$  indicate a probability of non-carcinogenic effects linked to the toxicity of GEM on human health. GEM values inside the *Herbarium* have been recorded every week from July 2020 to May 2021 using the Lumex RA-915M, a real time Hg detector. GEM concentrations refer to the working hours for *Herbarium* employers, from 09.00 A.M. to 17.00 P.M.

During the studied period, the model reveals an average *HQ* of 2.5, ranging within a minimum of 0.2 and a maximum of 7.6, with a sequence in the following order (averages values):  $HQ$ -spring <  $HQ$ -winter <  $HQ$ -autumn <  $HQ$ -summer. The highest value reached during summer displays an average *HQ* of 5, while the lowest is achieved during spring with an average *HQ* of 0.5. Based on the parameters considered in this study, like the exposure time and frequency, the GEM concentration at which  $HQ = 1$  (threshold level) is reached at a daily average GEM concentration of about 1650 ng/m<sup>3</sup>, significantly lower than almost all the recommended exposure levels and occupational exposure limits for airborne Hg compounds.

The results reveal a potential risk for *Herbarium* workers throughout the year, strongly influenced by the seasonality of the pollutant concentrations and therefore to the temperature variations, both outdoor and indoor. The risk associated with GEM levels inside the *Herbarium* is overestimated with respect to the Italian workplace legislation whose legal limits are 20000 ng/m<sup>3</sup>, time-weighted average 8-h per day, 5 days per week.

## **Gaseous mercury evasion from the water-air interface at freshwater environments impacted by different anthropogenic sources**

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*Keywords:* Mercury, contamination, flux chamber, water-air exchange, evasion.

The gaseous exchange of mercury (Hg) at the water-air interface represents an important aspect of the biogeochemical cycle of this element in the environment. Particularly at sites impacted by Hg due to anthropogenic activities, evasion can contribute to reduce the amount of this metal in the water column, but also to widen its spreading in the environment due to the long-range atmospheric transport of the element (Driscoll et al., 2013). However, dynamics of gaseous elemental Hg emissions from the water-air interface at Hg contaminated sites are still poorly characterised. In this work, Hg evasion fluxes were monitored by means of a flux chamber coupled with a real-time gaseous Hg analyzer (Lumex RA915M) in 3 freshwater environments characterized by different contamination legacy: the artificial reservoir of Solkan (SK-Slovenia) along the Isonzo River, where Hg contaminated sediments due to cinnabar extraction activities at the Idrija Hg mine have been accumulated since 1984, date of the dam construction; the dock near a chlor-alkali plant at Torviscosa (TR-Italy); the Cavazzo Lake (CV-Italy), chosen as pristine environment with no known Hg sources. At each site, 6 distinct sets of flux measurements were performed at regular time intervals during the diurnal period in 3 different seasons (spring, summer, and autumn). Moreover, the concentrations of dissolved gaseous mercury (DGM) were monitored during the sampling period together with total dissolved Hg, incoming UV radiation and main water physico-chemical parameters. As expected, at all sites the highest Hg fluxes were found in summer, due to higher irradiation, which favours the formation of volatile DGM through photoreduction, and higher water temperatures, which decrease the solubility of Hg. On average, Hg evasion fluxes found in this study were higher than those reported in literature for other background freshwater environments. Surprisingly, Hg fluxes at CV site were comparable to those of the other sites, likely due to re-emission of Hg of atmospheric origin, but further research is needed to confirm this hypothesis. The widest diurnal variability of Hg fluxes was observed at TR site, located inside an industrial complex, and likely related to irregular supplies of Hg through atmospheric depositions and water circulation. Conversely, SK and CV showed a more regular trend, confirming that Hg fluxes are strongly influenced by local conditions and site-specific interaction of different factors. Based on these results, the investigated sites can be considered as secondary sources of Hg for the atmosphere, underlining the importance of direct Hg fluxes monitoring to understand its fate in the environment.

Driscoll C.T., Mason R.P. Chan H.M., Jacob D.J. & Pirrone N. (2013) - Mercury as a Global Pollutant: Sources, Pathways, and Effect. *Environ. Sci. Technol.*, 47, 4967-4983.

## Low resilience of a mercury mining area after reclamation: the case of the Siele mine (Mt. Amiata Mining District, Italy)

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*Keywords:* mine, resilience, contamination, Monte Amiata, Paglia-Tiber River system, Hg<sup>0</sup>.

The Siele mine and its smelting plant are part of the world class Monte Amiata mining district (MAMD – Tuscany, Italy). The mine is located close to the Siele creek (c.), which drains the mining area, then flows to the Paglia River (R.), which in turn is an affluent of Tiber River, flowing through the city of Rome to the Mediterranean Sea. After closure in 1981, the mining area was subjected to the first reclamation in the district (and at the worldwide scale), completed in 2001.

In this study, we present new data on Hg concentrations in soils, stream sediments, and air in the Siele mining area and along the Siele c., and we review all previously available data, with the aim of quantifying the Hg contribution from the Siele c. into the Paglia R., and of documenting the evolution of the system following mine reclamation.

Hg concentrations (up to 5400 mg/kg) in stream sediments are comparable to pre-reclamation values in the first 500 m downstream the mine site. They decrease downstream to the confluence with the Paglia R., but remain anomalous (i.e., above the 1 mg/kg Italian law limit for residential soil). Comparison of pre- and post-remediation data of gaseous elemental mercury (GEM) in air shows that Hg<sup>0</sup> emissions in most of the sites within the Siele mining area are lower than pre-reclamation values, but in few outdoor sites, levels are still high (up to 9500 ng/m<sup>3</sup>), exceeding the existing regulatory limits (“Norma Amiata”: 300 ng/m<sup>3</sup> in outdoor sites). On the other hand, Hg mobility, determined by leaching tests, is mostly below the limits defined by pending regulations (1 µg/L), and methyl-Hg concentrations are mostly below 1 ng/kg (with a single value of 6 ng/kg).

Results show the Siele c. plays a role by no means negligible in the general picture of the contributions of Hg in the Paglia R. basin, proving to be one of the most critical areas of the entire MAMD. Indeed, concentrations of Hg in sediments and soils in the Siele c. are comparable to those of the Pagliola c., draining the Abbadia S.S. mine (the main site of the MAMD), where reclamation is still under way. Moreover, despite remediation works, Hg emissions from contaminated soil will represent a significant contribution to the atmospheric load of Hg in the future, if no further remediation action is taken.

The Siele system has a low resilience and natural recovery will take many years (probably decades), during which the area will remain an important source of Hg for the Paglia and Tiber River systems, and eventually for the Mediterranean Sea.

This study provides important background data for local authorities to implement monitoring strategies and find new remediation plans based on the identified critical area. Further, at a global scale, this work contributes additional data to the assessment of the global Hg budget to the atmosphere and the hydrosphere.

## The potential wildfire effects on mercury remobilization from soil and biomass in the Mt. Amiata mining district

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*Keywords:* wildfire, biomass, Mt. Amiata, mercury.

Natural wildfires are responsible for ~10% of total mercury (Hg) emissions to the atmosphere due to Hg volatilization from the tree biomass and Hg thermal desorption from soils. Mercury geochemical anomalies, such as Hg mining areas, utmost contribute to these emissions due to the occurrence of high Hg concentrations in vegetation and soil. Climate changes, increasing the occurrence of wildfires, are expected to further exacerbate this process, providing spikes of Hg concentrations in the atmosphere, possibly near to human sensible sites.

In this study, we calculate the release of Hg by a hypothetical wildfire occurring in the Mt. Amiata Mining District (MAMD) in southern Tuscany (Italy), where past Hg mining affects local atmospheric Hg concentration. Bark (n= 25), wood (n=18), and leaves (n=3) of black pines (*Pinus nigra* Arn.) and chestnuts (*Castanea sativa* Mill, leaves were not considered due to winter sampling), were collected in two areas of the MAMD and in a background site in the Appennino Pistoiese (AP – 150 km from MAMD). The two MAMD areas (Abbadia San Salvatore, ABS and Vivo d'Orcia, VO) are located at increasing distance from the metallurgical site (1.5 and 3 km, respectively). The soil (top and sub) was collected (n=22) below trees at each location. For all plant portions we quantified: i) the Hg content; ii) the involved biomass by means of allometric equations, extrapolating the result to woodland areas of 630 m<sup>2</sup> and 1066 m<sup>2</sup> for ABS and VO; iii) the mass of Hg stored in each area. Topsoil and subsoil were similarly quantified for Hg and for Hg storage. To estimate Hg emissions during the wildfire we assumed that: i) barks and leaves release 100% Hg (complete burning); ii) only 20% of wood is combusted; iii) the topsoil burning releases 100% of Hg; iv) subsoil does not contribute to Hg emissions.

Mercury was measured by means of a direct Hg analyzer (DMA), based on EPA method 7473.

For all plant substrata, higher Hg contents were observed in pines with respect to chestnuts. At all sampling sites, Hg concentrations vary in the order soil > bark > leaves > wood, and especially high at ABS site. The calculated Hg storages (plant + soil) are 1375, 321 and 58 g/ha for ABS, VO, and AP, respectively.

At ABS, soils act as the major reservoir for Hg, trapping 90-95% of the total Hg/ha. Among biomass, wood is the major reservoir for Hg (56%) followed by barks (42%); leave contributions seem to be negligible (2%).

These findings should be included in the development of fire risk prevention strategies and for the implementation of existing fire management activities.



## Detecting Geochemical Regime Shifts in the compositional dynamics of the Tiber River waters (Italy)

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*Keywords:* regime shift, river chemistry, Tiber River, compositional data analysis.

River waters may respond gradually or suddenly to natural or anthropic disturbances by varying their chemical composition. Understanding the nature of these complex interactions plays a crucial role in our fast-changing planet threatened by climatic and human-induced changes. In this work, water chemistry is analyzed as a whole by focusing on its interconnections with hydro-litho-morphologic and anthropic pressures at a basin-wide scale. This implies the introduction of the concept of regime shift, which has been widely applied to study the resilience of ecological systems to environmental perturbations. We propose to transpose this idea to geochemistry by considering Geochemical Regime Shifts (GRSs) as abrupt and permanent changes in the system state (composition) of a given environmental media, triggered by external or inner perturbations (Gozzi et al., 2021). From this perspective, river water composition represents a response variable resulting from the synergic action of environmental drivers and catchment properties.

The aim of this study is to detect potential spatial GRSs in the water chemistry of the Tiber River, the third-longest Italian river. To reach this aim potential forcing variables (e.g. land use, terrain slope, human impact and lithology) were considered and estimated for all nested watersheds. Compositional Data Analysis, Robust Principal Component Analysis and score-distance graphs were used to explore data variability and the nature of driver-system state relationships. In the lower reaches, a potential regime shift was identified for major species suddenly changing the water composition from a relative prevalence of N-bearing species to that of Na<sup>+</sup> and Cl<sup>-</sup>. The regime shift scenarios described by Andersen et al. (2008) suggest that the observed shift might represent a threshold-like state response triggered by lithological forcing. Conversely, no abrupt changes were detected for trace elements which instead seem to respond gradually to environmental pressures. The research offers new perspectives for future studies and for a deeper understanding of the circumstances controlling river system's self-restoring capability.

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Gozzi C., Dakos V., Buccianti A. & Vaselli O. (2021) - Are geochemical regime shifts identifiable in river waters? Exploring the compositional dynamics of the Tiber River (Italy). *Sci. Total Environ.*, 785, 14726.



## **Arsenic and mercury mass loads released by the Fosso della Chiusa creek waters (Mt. Amiata, central Italy)**

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**Keywords:** Mercury, Arsenic, Mt. Amiata, surface waters, mass load.

The Mt. Amiata Hg-district (southern Tuscany, Italy) is dominated by the homonymous volcanic system (0.3-0.2 Ma) and it is well-known as a ‘*World class deposits*’ from where liquid mercury was produced by roasting processes of cinnabar (HgS). At least sixteen sites of HgS-rich ore deposits in a radius of about 20 km (i.e. Piancastagnaio, Pietrineri, Carpineto, Le Bagnore, Monte Labbro) were cultivated up to the early eighties. Among these mining sites, that of Abbadia San Salvatore was by far the most important, with galleries reaching 400 m depth and with a production of more 100,000 tons of liquid mercury. The underground water system is almost exclusively drained by the Galleria Italia circumneutral mine drainage, characterized by a Ca(Mg)-SO<sub>4</sub> composition and high concentrations of Fe, Mn and Al (18714, 493 and 487 µg/L, respectively) and dissolved CO<sub>2</sub>. This mine drainage is connected through the Fosso della Chiusa creek to the riverine network of Pagliola, Paglia and Tiber rivers, the latter crossing Rome before entering the Tyrrhenian Sea. The Fosso della Chiusa is a 2.1 km long creek with an average flow rate of 40 L/s. This work is aimed at: (1) characterizing the As and Hg concentrations in the different environmental compartments (waters, suspended material and sediments); (2) studying the factors that affect their mobility in the aqueous medium; (3) estimating the yearly loads of As and Hg discharged by the Fosso della Chiusa. Thirteen sampling sites, located at about 150-200 m each other, all along the Fosso della Chiusa were collected. At each site, the water physicochemical parameters were measured, stream sediments (with the exception of one) and water samples for the determination of the main cationic and anionic species and dissolved As and Hg were collected. At the input point and exit point of the creek, 2 L of water were filtered with the aim to collect the suspended particulate on cellulose filters and to measure the turbidity. The results confirmed the Ca(Mg)-SO<sub>4</sub> water composition, with the content of dissolved As varying between 12 and 0.3 µg/L, with a decreasing pattern along the creek, while the Hg values are swinging (between 0.1 and 2.8 mg/L) with higher values in central points of the creek. In the particulate fraction, Hg and As showed concentrations at the inflow and outflow sites of 52 and 4.7 mg/kg and 77 and 0.27 mg/kg, respectively. Sediments showed a linear decrease for As (from 336 to 7 mg/kg), while for the Hg is showed from 7.5 to 153 mg/kg without a specific trend. The mass load, computed by applying a 40 L/sec flow rate, released from the Fosso della Chiusa creek was of about 1.3 kg yr<sup>-1</sup> for Hg and 0.7 kg yr<sup>-1</sup> for As, these values being comparable with those calculated for the Bonanza mine (western Oregon, Gray et alii, 2012) and the San Carlos creek which drains the New Idrija Hg mine (California, Ganguli et alii, 2000).

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Gray J.E., Hines M.E., Krabbenhoft D.P. & Thoms B. (2012) - Methylation of Hg downstream from the Bonanza Hg mine, Oregon. *Applied geochemistry*, 27(1), 106-114.

## Geochemical characterization of water quality in karst systems of Greece

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**Keywords:** karst systems, trace elements, water quality.

Karst systems represent the main drinking water source for 20-25% of world's population, although covering only 7-10% of the global land surface (Ford & Williams, 2007). Karst aquifers are highly vulnerable to external pollution, so their protection and management is of critical importance to sustain water resources.

In Greece, starting from the 1970's, water demands for agricultural, domestic and industrial use increased significantly, mainly in coastal areas (Daskalaki & Voudouris, 2008).

The main Hellenic aquifers are hosted in alluvial deposits, in Neogene deposits and in carbonate rocks. The latter cover about 35% of the country and are located in Western, Central and Southern Greece (Daskalaki & Voudouris, 2008). Karst aquifers are developed in limestones and dolomites (Triassic – Cretaceous), and in marbles (Paleozoic – Mesozoic). Their hydrogeological behaviour is controlled by tectonic deformation. About 45% of them is located inland, while the rest is in coastal areas (Voudouris & Kazakis, 2018).

During several field sampling campaigns from 2016 to 2020, 126 karst water samples were collected in Greece. Physicochemical parameters (temperature, pH, electric conductivity and redox potential) were measured *in situ*. Analyses of major ions and trace elements were performed at the laboratories of INGV-Palermo. Results were compared with the limits set by the Directive 98/83/EC that fixes quality standards for drinking water.

Temperatures of sampled waters ranged from 8.7 to 31 °C, pH from 6.5 to 8.4, whilst Total Dissolved Solids from 206 to 25,617 mg L<sup>-1</sup>. Most of the samples showed a typical alkaline-earth bicarbonate composition, whilst those sited along the coastline presented elevated concentrations of Na<sup>+</sup> (up to 7,680 mg L<sup>-1</sup>), Cl<sup>-</sup> (up to 14,200 mg L<sup>-1</sup>) and SO<sub>4</sub><sup>2-</sup> (up to 1,940 mg L<sup>-1</sup>), sometimes exceeding the EC limits, suggesting a seawater contamination. Furthermore, karst springs contaminated by seawater, displayed high concentrations of B (up to 3,870 µg L<sup>-1</sup>) and Sr (up to 7,080 µg L<sup>-1</sup>).

Nitrate concentrations were always below the EC limit (50 mg L<sup>-1</sup>), indicating a low contamination from fertilizers. Few low chloride waters showed a metal enrichment, such as Tempi springs (Thessaly) that presented enrichments in Sr (up to 242 µg L<sup>-1</sup>), Mo (up to 2.27 µg L<sup>-1</sup>), Cs (up to 1.57 µg L<sup>-1</sup>) and As (up to 17 µg L<sup>-1</sup>). Such enrichments could be attributed to the local petrological environment.

Generally, karst water samples can be considered suitable for human consumption. Water quality degradation of Hellenic karst springs is mainly due to seawater intrusion or to local geogenic contamination.

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Daskalaki P. & Voudouris K. (2008) - Groundwater quality of porous aquifer in Greece: a synoptic review. *Environ. Geol.* 54, 505-513.

Voudouris K. & Kazakis N. (2018) - General characteristics and classification of karst aquifers in Greece. *Review Bulg. Geol. Soc.*, 79(3), 159-160

## Natural and anthropogenic contributions of heavy metals from surface waters and suspended solids from the Valdinievole sub-basin (Tuscany, Central Italy)

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Keywords: water geochemistry, heavy metals, isotopes, Valdinievole.

The Padule di Fucecchio (Tuscany, Central Italy) is a protected swampy zone that has an important role in the migratory routes of several bird species. It is located in the lower reaches of the Valdinievole sub-basin and is fed by a relatively complex riverine network mainly consisting of the Nievole, Pescia di Collodi, and Pescia di Pescia rivers as well as numerous artificial canals that collect urban and industrial wastewaters from the densely inhabited and industrialized surroundings. The Usciana River represents the only emissary of the Padule di Fucecchio and, after 25 km, it flows into the right bank of the Arno River. Many relevant anthropic activities and small-medium enterprises, such as paper mill industries, flora-nursery farms, thermal spas, and one of the most productive Italian tanning districts, are present in the investigated area, making this zone one of the most polluted districts of the Arno River. In order to evaluate the presence of anthropogenic and natural contributions in the surface waters and suspended solids load of the Valdinievole sub-basin, this study is aimed at determining the seasonal variations in terms of main, minor, and trace elements by the analysis of 36 sampling points, distributed along an area of about 320 km<sup>2</sup> by Ionic Chromatography (IC) and Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the Department of Earth Sciences (University of Florence). Furthermore, the Sr and Pb isotopic ratios on water and suspended solid load samples by Thermal Ionization Mass Spectrometer (TIMS) to discriminate natural and anthropic sources are presently in progress. According to the geochemical survey carried out in March 2021, the water chemistry showed a relatively wide compositional variability, being comprised from Ca<sup>2+</sup>(Mg<sup>2+</sup>)-HCO<sub>3</sub><sup>-</sup> to Na<sup>+</sup>-Cl-(SO<sub>4</sub><sup>2-</sup>). The concentrations of the N-bearing species were up to 36 (NO<sub>3</sub><sup>-</sup>), 2.4 (NO<sub>2</sub><sup>-</sup>) and 11.5 (NH<sub>4</sub><sup>+</sup>) mg/L while the contents of Mn, Fe, and Cs were up to 595, 432, and 36.7 mg/L, respectively. As far as the concentrations of metals in the suspended solids, Cr and Zn presented the highest values, being up to 429 and 409 mg/kg, respectively. Nickel, V, Pb, Cs, and As showed contents up to 120, 149, 83, 46, and 25 mg/kg, respectively. It is mentioned that Cr shows a positive correlation with V and Ni, although enrichments in Cr were recorded in those samples close to the tanning district. The preliminary chemical data are clearly suggesting, as expected, the strong anthropogenic pressure acting on the Valdinievole sub-basin, which is in its turn reflecting into the Arno River water.

## Using Radon as a natural tracer for NAPL (MTBE and total hydrocarbons) contamination: a case study in Roma (Italy)

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*Keywords:* geochemical tracer, contamination, radon, NAPL, MTBE, monitoring.

Radon is a radioactive gas naturally occurring in soils and groundwater. It was used as a natural tracer for Non -Aqueous Phase Liquids (NAPLs) contamination, since it is much more soluble in a wide range of these substances than in air or water, resulting in a concentration-deficit compared to background values in nearby unpolluted areas. The mapping of this process, known as the “radon deficit technique” (Semprini et al., 2000) allows identifying the contamination by NAPL which affects both the vadose zone and the phreatic zone of an aquifer. This technique was applied to a contaminated site in Roma (Italy). In the site there is a gas station, where more than twenty years ago the first oil spill occurred with other episodes over time. The remediation of the area began in 2016 when a network of sampling wells was set up to monitor the extent and evolution of the contamination. The remediation system consists of pumping wells of the “pump & treat” system and injection wells for the reintroduction of treated water. A soil vapour extraction system completes the remediation plant. The main residual NAPLs in the site are total hydrocarbons expressed as n-hexane and Methyl-Tertiary-Butyl Ether (MTBE), a water-soluble additive. The monitoring activities included five sampling campaigns of water from the piezometers from February 2020 to May 2021. Radon measurements were collected with the radonmeter Rad7 (DurrIDGE Company Inc.) equipped with the Big Bottle RAD H2O accessory. Concentration maps, produced using radon data from water analyses, allow observing the gas concentration distribution in the waters of the sampled piezometers. The results show that the radon deficit accurately traces the location of NAPLs in the gas station, with a residual source zone extending in the NNW-SSE direction, following the flow direction of the aquifer. A good correlation between a low radon concentration and a higher presence of NAPLs was found. Finally, the presence of underground cavities around the study site, which could affect the circulation of fluids in the subsoil, is known by previous works (Nisio et al., 2017). Therefore, in order to deepen the study of the area surrounding the contaminated site, it was decided to carry out measurements of total gamma radiation, with a gamma detector.

Nisio S., Allevi M., Ciotoli G., Ferri G., Fiore R., Lanzini M., Roma M., Paolucci R., Stranieri I. & Succhiarelli C. (2017) - Carta delle cavità sotterranee di Roma.

Semprini L., Hopkins O.S. & Tasker B.R. (2000) - Laboratory, field, and modelling studies of Radon-222 as a natural tracer for monitoring NAPL contamination. *Transport in Porous Media*, 38, 223-240.

## Distribution of As, Hg and Sb in the mining waste dump of Abbadia San Salvatore (Mt. Amiata, central Italy)

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Keywords: Mercury, Arsenic, Antimony, Mt. Amiata, waste dump, soils.

Between the '50s and '60s, at the Lame dumping area of Abbadia San Salvatore mine (Mt. Amiata Hg-district), calcines, locally named "rosticci", after ore processing activities, were accumulated. In this work, top-soils and one calcine from this area were analysed for total and leached (with CO<sub>2</sub>-saturated MilliQ to simulate the effects deriving by soil-meteoric water interactions) concentration of As, Hg and Sb. In the waste top-soils, the contents of As, Hg and Sb were up to 616, 1910 and 1610 mg/kg, respectively whereas the lowest values were found in the calcine. Statistical analysis and thematic maps show that As and Sb have a similar distribution and two distinct populations were recognized, as follows: i) low-to-medium concentrations (10-33.8 and 0.18-62.50 mg/kg, respectively), located in the southern part of the dumping area and ii) high values in the northern portion. A different behaviour characterizes Hg since a single population is highlighted, showing how medium-to-high concentrations are distributed over the whole dumping surface.

The As, Hg and Sb contents of the leaching tests were compared with those imposed by the Italian Legislative Decree 152/2006 for drinking waters. Nineteen samples out of 35, 1 out of 35 and 16 out of 35 exceeded the legal limits for As, Hg and Sb: up to 102, 7.7 and 662 µg/L, respectively. In order to assess: i) the speciation of As, Hg, Sb in the CO<sub>2</sub>-rich aqueous solution and ii) which of the three chalcophile elements are preferentially partitioned in solution or tend to co-precipitate with other minerals, simulations with PHREEQC software were carried out. Arsenic, Hg and Sb occur as HAsO<sub>4</sub><sup>2-</sup>, H<sub>2</sub>AsO<sub>4</sub><sup>-</sup> and CaAsO<sub>4</sub><sup>-</sup>, Hg<sup>0</sup>, SbO<sub>3</sub><sup>-</sup>, Sb(OH)<sub>6</sub><sup>-</sup> and CaSb(OH)<sub>6</sub><sup>+</sup>. The solubility of Fe-oxy-hydroxides, which adsorb As and Sb, is apparently governed by that of magnetite (Saturation Index, SI=16). In the presence of pH>8, precipitation of calcite may be occurring. Thus, As and Sb could be hosted in the CaCO<sub>3</sub> lattice, precipitating as calcium arsenate (CaAsO<sub>4</sub>) and romeite (Ca<sub>2</sub>Sb<sub>2</sub>O<sub>7</sub>) may form over calcite crystals, respectively. In the Eh-pH diagram, As is present as HAsO<sub>4</sub><sup>2-</sup>, that is mainly adsorbed by Fe-oxy-hydroxides. All Sb compounds are found close to the stability range of tripuhyte (FeSbO<sub>4</sub>) and romeite. Tripuhyte is not found as the main mineral because it is likely that part of hosted-Fe<sup>2+</sup> precipitating as Fe-oxy-hydroxide. Nevertheless, its presence was confirmed by various simulations where SI was clustering around 2. A detailed mineralogical study of the top-soils is required to confirm the presence of tripuhyte although its content is expected to be very low. Finally, the main Hg species is Hg<sup>0</sup>, although a minimal decrease in pH allows Hg entering the stability range of HgS. This can be attributed to the leachate acidity (ca. 4.3), which favours the solubilisation of Me-sulphides occurring in the soils and consequent re-precipitation of As, Hg and Sb as sulphides, which decrease their content in solution.

## Heavy metals contamination in road dust and tree barks in the urban area of Firenze (Italy)

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*Keywords:* urban geochemistry, road dust, tree barks, heavy metals, Firenze.

Nowadays, more than half of the global population lives in urban areas, a fraction which is expected to increase up to 68 % by 2050. Urbanization deeply modifies the environment through natural resources consumption, waste production, gas emissions, and air, water and soil pollution. Heavy metals (HMs) deriving from human activities are one of the most critical aspect of urban contamination.

Road dust (RD) - i.e., the powders or dirt aggregates found on roads - concentrates HMs from different sources like fossil fuel combustion, non-exhaust vehicle emissions, weathering of buildings and pavements, and atmospheric deposition. Because of its short residence time on roads (150-250 days), monitoring RD may represent a relatively quick tool for implementing strategies to mitigate urban contamination. Among the latter, green infrastructures have been demonstrated to efficiently improve air quality, acting as barriers to particulate matter.

In this study, RD and tree barks from busy traffic roads in the city of Florence (Italy) were quantified for HM for the first time. Areas with intense traffic, close to traffic lights and with low traffic were selected to compare different states of pollution.

Concentrations of common heavy elements (Cu, Pb, Zn, Sb) were determined by aqua regia digestions and analysed by ICP-OES, while Hg was quantified by a Direct Mercury Analyzer (DMA) in RD samples. Barks were collected from two dominant species of trees bordering the main roads, the pine (*Pinus pinea*) and plane tree (*Platanus x acerifolia*), in proximity to RD collection sites and characterized for Hg contents. Other trace elements are under analysis.

In the RD, concentrations of Cu and Zn exceeded the limits set by the Italian legislation for residential use soils (120 and 150 mg/kg respectively; CSC, Column A, D. Lgs.152/2006) at almost all the investigated sites. Cu and Pb were above the limit for commercial and industrial use (600 and 1000 mg/kg, Column B, D. Lgs.152/2006) at two high congested sites. The RD collected in a city park, selected as a “blank” site, showed the lowest concentrations of metals as well as the lowest concentration of Hg (43 mg/kg), while the highest Hg value was found in the city centre (110 mg/kg). Mercury concentrations in tree barks were consistent with the results obtained in the RD, with pine trees displaying the higher Hg concentrations with respect to the plane tree at all sites.

Preliminary results showed that HMs levels in RD were highly related with cars traffic volume. Samples collected close to traffic lights showed elevated levels of metals, compared to sites with low flowing traffic. Further work should be performed to differentiate contamination sources, and to characterize different tree species as a potential tool in highly traffic impacted roads. Overall, the preliminary outcome of this study suggests that evergreen species should be preferred compared to deciduous species in city management to improve air quality.



## **Physical pollution of karst aquifers caused by marble quarrying: the case of the Apuan Alps, Italy**

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*Keywords:* Carrara marble, marble powder, karst aquifer, water quality.

The Apuan Alps are a mountain range in northern Tuscany exploited for the famous Carrara marble since the Roman age. The Apuan quarrying district currently comprises about 150 quarries and most of them are located at high elevations. Marble blocks are cut and re-squared by means of line drilling and various sawing techniques, diamond wire and chain saw being the most used. Such quarrying activities produce a fine marble powder that frequently mixes up with meteoric water, producing a slurry that can easily infiltrate into the karst aquifers through solution-enlarged fractures. Depending on the aquifer hydrodynamics, the marble slurry can eventually reach the karst springs, thus contaminating high quality waters generally used for the human consumption. Several samples of marble powder, karst spring deposits, and stream sediments were collected and analyzed for their mineralogical, morphological and sedimentological characterization, to evaluate the degree of pollution of the Apuan karst aquifers. Quarry powder samples are mainly made up of calcite crystals, whereas spring and stream sediment samples have variable proportions of calcite, silicates, and dolomite grains. The clasts from marble powder produced by diamond wire and chain sawing have constant morphological features, whereas the sediments collected in filtering tanks and disposal bags exhibit more heterogeneous characteristics. The quarry powders are generally finer than the sediments, although some overlap occurs probably because of marble powder contamination in the sediments themselves. The most polluted spring samples are characterized by a predominant calcite component that is finer than the silicate one. The same occurs also for the stream samples. Spring samples also show homogeneous morphometric features that are probably related to both marble powder contamination and the transport mechanisms through the karst aquifers. Marble powder pollution appears to be widespread in most of the Apuan karst springs, thus affecting the aquifer hydrodynamics and water quality.



## Mercury in the water column of the Gulf of Trieste is still an environmental issue: the legacy of the Idrija mine twentyfive years after its closure

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Keywords: mercury, water column, suspended particulate matter, sediments.

Mercury (Hg) contamination in the Gulf of Trieste (GT, northern Adriatic Sea) is due to historical mining activity at Idrija (Slovenia) and still represents an environmental issue of great concern (Covelli et al., 2001; Covelli et al., 2021). Indeed, the freshwater inputs from the Isonzo/Soča River have been identified as the main source of Hg into the GT. At the river mouth, the element was found to be mainly associated with the suspended particulate matter, especially following periods of medium-high river discharge and river plume events in the GT (Covelli et al., 2006; 2007)

The primary aim of this research is to evaluate the occurrence and distribution of both dissolved (DHg) and particulate (PHg) Hg along the water column in the northernmost sector of the GT, a shallow and sheltered embayment suitable for the accumulation of fine sediments and contaminants. In order to achieve this objective, sediment and water samples were collected at six sites which were representative of different targets, such as mussel farming and tourism activities. Moreover, different environmental conditions including unperturbed and perturbed hydrological conditions, induced by both natural and anthropogenic factors, were taken into account.

The amount of Hg in the surface sediments ( $0.77\text{--}6.39\ \mu\text{g g}^{-1}$ ) as well as the relationship between the Hg concentration and the percentage of the 2-16  $\mu\text{m}$  grain size fraction from this study were found to be consistent with previous research focused on the whole Gulf, thus testifying the common origin of the sediment.

Results showed a notable variability of DHg ( $0.07\text{--}149\ \text{ng L}^{-1}$ ) and PHg ( $0.39\text{--}12.5\ \text{ng L}^{-1}$ ) depending on the interaction between riverine and meteo-marine hydrological conditions at the time of sampling. Mercury was found to be mainly partitioned in the suspended particles and elevated values of PHg were observed following periods of high discharge from the Isonzo/Soča River confirming that the river discharge may represent an important factor in regulating the amount of PHg in the GT.

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Covelli S., Petranich E., Pavoni E. & Signore S. (2021) - Can Sediments Contaminated by Mining be a Source of Mercury in the Coastal Environment Due to Dredging? Evidence from Thermo-Desorption and Chemical Speciation. *B. Environ. Contam. Tox.* In press. <https://doi.org/10.1007/s00128-021-03159-x>.

## Dissolved nitrates in the lower Metauro River aquifer (Marche Region, central Italy): a long-lasting story

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Keywords: Nitrate pollution, groundwater, Metauro river.

Large volumes of water resources at global level are seriously affected by nitrate contamination, mainly due to an exaggerated use in agricultural practices. The most impacted waters are those forming surface bodies and shallow reservoirs, the latter mostly hosted in alluvial plains, where highly permeable deposits are usually dominating. These aquifers play a key role in supplying waters to civil, agricultural, and industrial activities.

Nitrate pollution by diffuse sources was first targeted in Europe by the Nitrate Directive (91/676/CEE) and subsequently by the Water Framework Directive (2000/60/EC), which also defined the “Nitrate Vulnerable Zones”, which are intended to be territories that drain nitrate polluted (or at risk of pollution) waters. Concerning the shallow aquifers, NO<sub>3</sub><sup>-</sup> vulnerable zones were identified as those containing, or that could be containing, > 50 mg/L of NO<sub>3</sub><sup>-</sup>, as specified by the Italian Law Decree 152/2006 (modified and integrated by the L.D. 30/2009). Accordingly, the administration of the Marche Region (central-eastern Italy) has declared the Metauro river plain (located in the northern part of the region) that hosts a phreatic aquifer, as highly vulnerable by nitrates.

In this work, the terminal portion of the fluvial plain was investigated during three hydrogeochemical surveys (June 2019, September and November 2020), in the framework of the bilateral Interreg Italy-Croatia project ASTERIS: *Adaptation to Saltwater intrusion in sEa level RIse Scenarios*. Although the main target of the project was dedicated to the interaction between fresh and saline waters, strikingly high nitrate contents (up to 104 mg/L) in the phreatic aquifer were determined, and in more than a half of the studied waters the NO<sub>3</sub><sup>-</sup> concentrations resulted to be >50 mg/L. Historical data available from 2009 confirm that most of the monitored wells maintained high NO<sub>3</sub><sup>-</sup> concentration levels up to today. The high NO<sub>3</sub><sup>-</sup> concentrations strongly limit the water exploitation potential by the local water supply company for drinking purpose and the waters from the Metauro river, whose NO<sub>3</sub><sup>-</sup> content is <8 mg/L, are injected into the shallow aquifer in the inner part of the valley. Despite the large amount of river water driven underground, the dilution effect is only detectable in limited portions of the territory where the NO<sub>3</sub><sup>-</sup> contents are below the normative level. It is to note that NO<sub>3</sub><sup>-</sup> shows a dramatic decrease downstream the reinjection site and near the Metauro river, suggesting river-aquifer exchanges. The NO<sub>3</sub><sup>-</sup> pollution is a long-lasting story since nitrate started to increase in the seventies but interventions to reduce the nitrogen loads on the ground and the adopted measures aimed at the protection of aquifers did not produce satisfactory results. This implies that mapping spatial and temporal variations of NO<sub>3</sub><sup>-</sup> concentrations is of paramount importance to detect the most critical areas where to intervene.

## **The Geochemical Numerical Model of Liguria: a stochastic tool to evaluate the uncertainty of elemental concentration estimates**

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*Keywords:* geochemical baselines, stream sediments, geochemical numerical model, stochastic approach, uncertainty.

Stream sediments have intrinsically the capability to describe the geochemistry of the sample's upstream basin, averaging each elemental contribution of the different outcropping lithotypes.

Finer fraction (<150 µm) is used as indicator of landscape status respect to pollutant, because of high reactivity with surficial water, groundwater and biota in a long-term environmental monitoring. Furthermore a sampling point on a stream network shows a nearly stable composition under the assumption of watershed time/space stationarity.

Aside it is useful to underline that hot topic in environmental geochemistry is the definition of wide-area elemental background concentration value in geological matrixes. Moreover it is often mandatory for regulatory activities to define local elemental reference values over a discrete area to be compared to point concentration. This need is strictly related to a change of support passing from point measurement to evaluation over a representative area unit.

Ultimately those reference values in whatever manner are defined over heterogenous geological settings can reach limit of applicability or worst overused if not defined in a probabilistic frame. The heterogeneity of the Ligurian Alps and Appennines invokes a change of strategy for what concerns the description of the spatial distributed geochemistry capturing the local variability of the regolith composition. With the aim to develop a flexible and highly adaptive tool based on geostatistical approach, the Geochemical Numerical Model of Liguria (GNM-L) of stream sediments is created.

That digital product is the result of a joint project of the Regione Liguria and DISTAV to generate a tool able to fix the geochemistry of the environment based on stream sediments and to become a reference layer for future environmental intervention.

To manage lithotypes heterogeneities computations are led on a-priori defined irregularly shaped discrete mosaic of the Liguria with the development of a geostatistical knowledge of regional variability.

The database used to compute the spatial patterns of 32 elements by means of 8 statistical moments and probabilistic cut points of distribution functions is composed by 1830 sampling stations along the stream network.

Each of them are sampled with a quasi-random sampling schema based on a subset of the grid GRID generated as a reference layer during the creation of the Archivio Geochimico Nazionale in the frame of the ANPA-CNR-UNIGE joint project.

Through the application of a stochastic method based on gaussian sequential simulations over a multi resolution grid computation each chemical element is deeply investigated as a random function on a final support of 200m x 200m.

The enhancement of the information density on each single element of the GNM allows the end-user to understand more profoundly the environment with the help of a sufficiently flexible tool that more adherently can represent the point uncertain reality.

## Potentially toxic elements (PTEs) associated with asbestos chrysotile, tremolite and actinolite in the southern Apennines (Italy)

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*Keywords:* asbestos, NOA, toxic elements, trace elements, southern Italy.

Now a day, it has been well established that asbestos fibres can pose a serious health risk since they host potentially toxic elements (PTEs), which are known to induce noxious effects. In order to understand how these elements contribute to asbestos-related diseases, the present contribution quantifies and compares PTEs in terms of major, minor and trace element concentrations (e.g. Si, Mg, Ca, Fe, Mn, Al, Ti, Cr, Ni, Co, Cu, Zn, V, Ti, Be, As, Rb, Sb, Ba Sr, and Pb) in various types of asbestos-minerals occurring in the ophiolite terranes of the Southern Apennines (Basilicata and Calabria regions, southern Italy). To this aim, we used various techniques such as X-ray micro-fluorescence energy dispersion ( $\mu$ -XRF), inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma spectroscopy with optical emission spectrometry (ICP-OES).

Attention focused on chrysotile, asbestos tremolite and asbestos actinolite extracted from the Gimigliano-Mount Reventino Unit (Calabria region; Bloise et al., 2016; 2020; Punturo et al., 2015) and from Episcopia and San Severino Lucano villages (Basilicata region; Punturo et al., 2019).

Results showed significant and variable amounts of Cr and Ni as well as other potentially toxic elements such as As, Co, Cu, Zn, V and Pb as well as other metals such as Mn and Fe (minor elements): all of these elements are known to induce toxicity, whose negative effects are well recognized.

Furthermore, the potential leaching of PTEs released by asbestos-containing rocks into the soil and water supply is also presented and discussed. Since asbestos fibres can be widespread in the environment (i.e. rocks, soil, water) and thus encounter the human body, it is essential to quantify the toxic elements present in asbestos fibres in order to prevent asbestos-related diseases. The knowledge obtained from this study will provide us with a better understanding of asbestos-related diseases.

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Punturo R., Ricchiuti C., Bloise A. (2019) - Assessment of serpentine group minerals in soils: A case study from the village of San Severino Lucano (Basilicata, Southern Italy). *Fibers*, 7(2), art. no. 18.

Bloise A., Punturo R., Catalano M., Miriello D. & Cirrincione R. (2016) - Naturally occurring asbestos (NOA) in rock and soil and relation with human activities: The monitoring example of selected sites in Calabria (southern Italy) *Italian Journal of Geosciences*, 135(2), 268-279.

Punturo R., Bloise A., Critelli T., Catalano M., Fazio E. & Apollaro C. (2015) - Environmental implications related to natural asbestos occurrences in the ophiolites of the Gimigliano-Mount Reventino unit (Calabria, Southern Italy) *International Journal of Environmental Research*, 9(2), 405-418.

## **S15. Coastal erosion**

*CONVENERS AND CHAIRPERSONS*

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*Renata Archetti (University of Bologna)*

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## Shoreline and environmental changes detection in the gulf of Gela, southern Sicily (Italy)

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*Keywords:* shoreline evolution, dune fragmentation, DSAS, coastal armoring.

The Gulf of Gela coincides with the second-order coastal sub-cell n. 4.2 identified by the Regional Plan against Coastal Erosion and falling within the first order coastal sub-cell that extends from Capo Passero Island to Capo San Marco (Regione Siciliana, 2020). The main focus of the study is the shoreline evolution of the Gulf over long- and medium-term periods. The level of fragmentation of the dune systems (Moline et al., 2020) and the impact of coastal works (Aybulatov & Artyukhin, 1993) have been assessed as well and related to the coastal variations. The image analysis has been performed using a heterogeneous cartographic dataset, like IGM aerial photographs (1955, 1966), orthophotos of the National Geoportal (1989, 2000, 2006, 2012), Google Earth images (2016), and UAV (Uncrewed Aerial Vehicle) image acquired in 2018. The Digital Shoreline Analysis System (DSAS), an application of the ESRI ArcGIS© software shorelines, was used to compute the statistical indexes (SCE, NSM, WLR) and assess the shoreline movements. The shoreline change analysis shows that the area close to the Southern Imera river mouth experienced severe landward migration over the medium term with a maximum negative rate of  $-3,59$  m/year. The medium-term analysis was confirmed by the long-term assessment with a maximum erosion rate of  $-6,37$  m/year recorded eastward the Southern Imera river mouth. The eleven breakwaters set few meters eastward the river mouth partly blocked the shoreline retreat and slight accretion has been here registered. However, the Shoreline Change Envelope (SCE) showed that the main depositional phenomena occurred over the time between 1955 and 1966, whereas progressive and constant landward migration has been observed between 1966 and 1989. Significant depositional phenomena were found up-drift the Scoglitti harbor where the northern dike has been repeatedly implemented and acted as sediment trap of the longshore drift. The area at the southern edge of the Gulf showed mainly a stable trend over the mid-term, but the long-term analysis and the SCE index revealed that accretion mainly occurred over the period between 1955 and 1989 and that the trend has changed between 1989 and 2018 when slight erosion phenomena have been recorded.

The study showed that the most intense erosion phenomena have been detected where the level of fragmentation of the dune systems and the coefficient of technogenesis impact is much higher.

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Molina R., Manno G., Lo Re C. & Anfuso G. (2020) - Dune Systems' Characterization and Evolution in the Andalusia Mediterranean Coast (Spain). *Water*, 12(8), 2094.

Regione Siciliana – Ufficio del Commissario di Governo contro il Dissesto Idrogeologico nella Regione Siciliana. 2020. Piano Regionale contro l'Erosione Costiera, versione 1.0, 1527 pp.

## Diachronic and environmental analysis in the Ragusa province, southern Sicily (Italy)

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*Keywords:* shoreline evolution, DSAS, land use change.

The present work was focused on the study of the shoreline evolution of the coastal area between Pozzallo (RG) and Santa Maria del Focallo (RG), in Southern Sicily (Italy) and on the image detection of the environmental changes that occurred between 1880 and 2016. The findings were used to identify which events triggered the erosional phenomena and to plan better solutions to mitigate the negative effects. The study combined the grain-size analysis of the beach sediments and the diachronic analysis of shoreline position detected in historical and technical maps, aerial and satellite photographs. The 1928 shoreline was used as baseline and 14 transects were cast orthogonal to the 1928 baseline. The shoreline rates of change were computed thanks to the Digital Shoreline Analysis System (DSAS), an application that works in a GIS environment. Natural (dune systems, coastal quagmires) and coastal infrastructures were identified in each available cartographic dataset and mapped for each year. The diachronic analysis highlighted a shift line speed between 2,6 m/y and -2,6 m/y and a range of shoreline movement between -130,5 m and 107,3 m. It was worthy to note that the Pozzallo port trapped the longshore sediment transport and shoreline has been significantly increasing of several meters over the last decades. However, eastward the Pozzallo port, Santa Maria del Focallo beach has been affected by severe erosion, both due to the Pozzallo port, which acted as sediment trap blocking the longshore drift from the west, and to the loss of the dune system, replaced by holiday houses or greenhouses. Moreover, the coastal ecosystem has been even affected by the loss of the natural coastal quagmires and the implementation of the coastal road (SP 67) few meters nearby the shore. The increasing urbanization and anthropization significantly changed the dynamic balance of the shore. Clear guidelines on the approach to tackle the problem are provided by the European Parliament in the Integrated Coastal Zone Management (GIZC) in Europe (European Council, 2002), which advises the need, on one hand, to promote integrated use of the coast, decreasing unauthorized building, and, on the other hand, to restore natural shore refilling, furthered by renaturalization of the dunes.

European Council (2002). Raccomandazione relativa all'attuazione della gestione integrata delle zone costiere in Europa (GIZC). G.U.C.E. Legge n. 148 del 06.06.2002.



## **Sedimentary evolution of a young tidal flat in the Northern Part of the Po Delta (Italy): a Strategy for Future Building-with-Nature Management**

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*Keywords:* tidal flat, salt marsh, wetlands, geomorphological changes.

According to a recent study based on analysis of long-term satellite imagery datasets (Ninfo et al. 2018), the Po river Delta (Northern Italy) started again a positive sedimentation trend and a constructive process is ongoing at the main river branches. New tidal flats are building up around the tip of the delta, where once agricultural fields were inundated by the strong floods of 1950-60. The evolution of these environments is comparable with recent restoration projects that took place for example in the Venice lagoon, indicating that this case study is a good example for considering future reconstruction of microtidal areas in a deltaic context. A young tidal flat of about 10 ha, located in the Northern part of the Po della Pila branch, was studied by fieldwork activities since October 2018. Morphological surveys, sediment distribution and sedimentary pattern were defined through UAV survey, coring and sediment traps. Moreover, the study was supported by an historical review of orthophotos from the 1950s till the present. The results show that an extended crevasse splay, which covers the central part of the flat, has developed from the early years 21st century, due to human intervention on levees as well as river floods. The tidal flat granulometry is predominately fine sediment (Silty clay and Clayey silt), except for the central area, where the sand percentage increases (Silty sand). Two subfacies were defined: the most surficial one reaches ~10 cm depth below the surface and it is characterized by coarser sediment in the central section of the tidal flat; instead, the sand percentage increases within the sediment column from ~10 to 25 cm next to the inlets. The study area experienced a positive sediment budget and it was characterized by higher rates of accretion after Po river floods. The deposition rates ranged from 0.5 to 3.3 g/m<sup>2</sup> per hour during two surveys of September 2019 and March 2021 but increased further from 1.9 to 20 g/m<sup>2</sup> per hour during the survey of June-July 2020. All these observations suggest that the tidal flat, as well as the southern part of the lagoon, is fed by sediment from the Po River branch, while the tide redistributes the sediment around the tidal flat. The work finally aims at comparing this case study with other tidal flats and salt marshes worldwide characterized by similar as well different tidal regimes, thus identifying the optimal elevation for vegetation to establish and flourish. This could support the future restoration projects of these environments.

Ninfo A, Ciavola P. & Billi P. (2018) - The Po Delta is restarting progradation: geomorphological evolution based on a 47-years Earth Observation dataset. Scientific Reports, <https://doi.org/10.1038/s41598-018-21928-3>.

## **Sandy coasts facing climate change: accommodation space and availability of strategic sediment reservoirs dictates adaptation approaches.**

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*Keywords:* beach, sediment, sea-level, climate change.

We inferred the morphological adaptation to climate change of 12 microtidal beaches located along the central-western coast of Sardinia. The studied beaches are barriers and beach-dune systems and are conditioned by geological control due to the presence of extensive rocky outcrops in the sea. The sediments are heterogeneous in composition and grain size, including relict siliciclastic gravels and coarse sands and biogenic carbonate sediments. We assumed that the landward beach migration, following sea level rise, will occur through roll-over of barriers or foredune erosion depending on the availability of enough accommodation space.

A digital terrain model derived from Lidar data (1 m of resolution) and geo-referenced aerial photos were used to evaluate the accommodation space available for inland beach migration following the expected relative sea-level rise at 2100. The surface of the backshore available for beach migration was mapped considering the backshore slope and the presence of hard structure (rocky outcrops and man-made structure) that prevent beach migration.

An analysis of the availability of compatible sediment reservoirs for possible beach nourishment was carried out. The availability of compatible sediments was determined by comparing sediment grain size and composition of beach and marine reservoir sediments, which were previously mapped along the ongoing continental shelf.

The results of this work show that the impact of global changes on beaches is highly site-specific. Particularly, beaches with low accommodation space in the backshore, which are bordered by cliffs or man-made structures, will be subjected to erosion for the impossibility to move backward. The analysis of the compatibility of beach sediments with submerged sediment reservoirs shows that, although large volumes of sediment are available, some of the beaches are composed of sediments not compatible with those present in the sea. The following management implications can be derived: (I) the impact of sea level change is site specific and cannot be predicted at global scale, but only considering the specific characteristics of each site; (II) the accommodation space, when available, must be preserved to allow the beach to adapt to sea level change; and (III) strategic sediment reservoirs must be identified and well-kept for the interventions that will become necessary in the future.

## **Uncertainty of UAV-derived DEMs and significance of detected morphodynamics: the case study of a scraped dune in the Northern Adriatic**

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*Keywords:* beach scraping, artificial dunes, unmanned aerial vehicles, photogrammetry, coastal geomorphology.

A morphodynamic study of a scraped artificial dune built on the sandy beach of Porto Garibaldi (Comacchio, Italy) as a barrier to protect beach facilities from sea storms during the winter season was implemented by analysing Unmanned Aerial Vehicle (UAV)-derived products, such as digital elevation models (DEMs) and orthophotos. The role of elevation data uncertainty and uniform thresholds for change detection (TCDs) on the interpretation of morphodynamic estimations related to non-extreme sea and wind conditions was analysed. The analysed DEMs showed a reasonable agreement with ground truth surveys (Global Navigation Satellite System, GNSS), with RMSE < 0.05 m. The significance of the identified changes was determined by applying a set of TCDs. In this case, a threshold of 0.15 m was able to detect the majority of the morphological variations. However, the set of TCD  $\leq 0.15$  m was considered to properly discuss the significance of minor changes and the uncertainty of volume change calculations. During the analysed period (21 December 2016–20 January 2017), while water levels and waves affected the front of the artificial dune by eroding the berm area, the aeolian forcing (i.e. winds) remodelled the entire dune, moving the loose sand around the dune and further inland. Notably, sediment volumes mobilised by sea and wind forcing were comparable. In the case of extreme storms, it is expected an important degradation of the dune while preserving the touristic concessions from flooding and beach erosion. It is suggested that UAV-derived coastal morphological variations should be interpreted by integrating a set of uniform thresholds to detect significant changes with the uncertainty generated by the propagation of the original uncertainty of the elevation products. Additionally, the characteristics of the morphodynamic drivers should be evaluated by adopting uncertainty-aware approaches. In this way, the contribution of subtle morphological changes, which magnitudes are comparable with the instrumental accuracy and/or the assessed propagated uncertainty, can be properly accounted for.

## **High resolution and automated monitoring methodology (UAV) for vegetation and morphological dynamics involved in restoration projects in coastal sand dunes environments.**

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*Keywords:* UAV, spectral firm, geomorphological analysis.

Nowadays, given their fundamental importance, the application of coastal sand dunes' restoration plans is widespread and they are usually aimed at reactivating the natural dynamics of two main components, often compromised: the morphological integrity and the vegetation growth. The aim of this work is to propose a relevant and low-cost methodology for monitoring this kind of restoration projects, which contemplates a simultaneous survey of the geomorphological component as well as the vegetational one. An Unmanned Aerial Vehicle (UAV) was applied to survey these two components' trend, by means of building high-resolution Digital Surfaces Models (DSMs) and RGB orthophotos, in an area in the North Adriatic Sea (Punta Marina, Ravenna, Italy): the local coastal environment is particularly suitable because it includes a residual coastal dune system, damaged by decades of erosion and fragmentation by human intervention. The area was recently the subject of a restoration project aimed at limiting its deterioration as well as enhancing dune stability by the construction of walkways and the introduction of vegetation. RGB data from the drone's photographs were used to identify the spectral signature of vegetation in the visible part of the spectrum as well as that of bare sand. This allowed to monitor changes in the relative cover area extension (vegetated Vs not vegetated) in time. Elevation data from high-resolution DSMs were used to identify and monitor changes (considering every source of error) of the principal morphological features, such as the Dune Foot Line (DFL), the Dune Crest Line (DCL), the Dune seaward Crest Line (DsCL) and the Stable Vegetation Line (SVL). Both morphological data, as well as orthophotos analysis, confirmed a constant and progressive increase of the vegetated cover area and consolidation of the dune system following the restoration project. The proposed survey protocol resulted to be rapid, low-cost and easily replicable by coastal managers to quantify the effectiveness of restoration projects.

## **Evidence of preservation of submerged sand banks: source-to-sink pathway enhanced by climate changes?**

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*Keywords:* sediment budget, barrier island, sand bank, climate change.

The foreseen global sea level rise threatens the most vulnerable coastal morphotypes, as the barrier islands. Their resilience is linked to processes of sediment deposition, mostly where a high sediment supply occurs, via a source-sink pathway or through cannibalization.

Along the barrier islands of the Grado Lagoon (North Adriatic Sea), a system of submerged sand banks (called Mula di Muggia Bank, MMB) extends up to 2 km seawards and their rapid evolution induces conflicts with the touristic uses of the adjacent beaches. In order to quantify the past and present morphological changes and obtain the sediment budget, this work compared the aerial photographs from 1954 to 2019 and topobathymetric data (1968, 1985, 2007 and 2019).

The temporal morpho-evolutionary analysis shows the preservation of a wide succession of intertidal and subtidal sandy bars, which migrate toward southwest. The migration follows the main littoral drift generated by waves along the sedimentary pathway of the only fluvial source, the Isonzo River. Down-drift, on the western terminus, the bank curves abruptly, inducing bars to shift landward toward the touristic beaches. Therein, sediment tends to accumulate over time, and the area is currently the final sedimentary sink for the entire coastal compartment.

The sediment budget from 1968 to 2019 confirms two markedly positive budget sectors: the eastern one, adjacent to the sedimentary source of the Isonzo River, and the westernmost sector, as the trap of the longshore littoral path. Conversely, in the central tract a stable budget would indicate an area of sediment bypass. Here, the deposition prevails on the shallow zone, whereas beyond the -2.5m depth an erosive dynamics occurs with an increase in the steepness of the bank's outer limit.

The causes of these complex dynamics are still unknown, but the role of a bimodal wave regime must be considered: it acts in the opposite way on the seabed at different depths. Moreover, the bimodal wave regime explains the landward shift of the sandy bars in the western area where the influence of the southern swell waves is greater.

Despite the cannibalization of the central tract, the very high positive budget resulting in the western sink area of the MMB (about 3 million m<sup>3</sup> in 51 years) is difficult to explain in the regional context.

In the lack of direct measurements, our hypothesis suggests the effect of climate changes in hydrological and solid regime of the fluvial source could exert a main role in the sedimentary dynamics. Longer summer drought and subsequent greater intensity of late autumn/winter precipitation likely lead to an increase of the Isonzo River solid discharge. Moreover, part of the sediments eroded by the deeper seabed could supply the sedimentary source of the Isonzo river delta, thus increasing the littoral drift.

## **Revalue historical data to overcome the persistent lack of long-term datasets in coastal geomorphology: examples from Northern Ireland.**

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*Keywords:* coastal geomorphology, coastal erosion, dune retreat, shoreline change, long-term data, historical data.

Research studies and numerical models in coastal geomorphology often rely on short to medium-term datasets (months to years), normally depending on available financial resources to enrol employees or adopt up-to-date surveying technologies. Lately, satellite images have largely benefit long-term analyses of coastal change, extending the temporal investigation up to few decades, but limitations related to temporal coverage and spatial resolution remain. An unexploited source of information is represented by historical data, but modern coastal geomorphologists do not take advantage of them due to their poor reliability and accuracy, especially if compared to modern technologies. The keynote will explore a new chance to build long-term datasets of coastal change through the revalue of historical data with modern techniques of Structure-from-Motion (SfM), GIS analyses and reliable estimation of spatial errors. Reliable geographic data were extracted from different sources available from historical archives (i.e., aerial photos, maps, bathymetric charts, topographic data pre-DGNSS era, military reports, newspapers, etc.) for the coastal site of Dundrum Bay in the Irish Sea (Northern Ireland, UK). Historical maps and aerial photographs were analysed to extrapolate 23 shorelines and quantify almost 200 years of shoreline change (1833 to 2020). Vertical aerial photographs were processed thorough SfM techniques to build 3D models and calculate volumetric change of the extensive local coastal dune for the last six decades (1963 to 2020). Geomorphic changes were discussed considering local forcing parameters (wave, wind, water level) from historical or hindcasted datasets available (1901 to 2020). Advantages and limitations of each ‘revaluation’ technique of the historical data were considered. Several potential errors are associated with historical coastal data; however, their advantage is to provide a quantifiable record when other (more accurate) data sources are not available. In the pre-satellite era (pre-1970’s), historical geographic data are the only available source, and they have also the advantage to be coeval with the increase of human pressure on the coast (post Industrial Revolution and post WWII). Long-term datasets are crucial for decision makers, often divided between warnings from the scientific community and the will to give effective and immediate response to concerns from the coastal communities. Adaptation strategies for coastal environments are often conceived without a long-term perspective which is partially caused by the lack of reliable long-term data. In a current situation of rapidly improving machine learning techniques, reliable long-term datasets are crucial to feed algorithms and better refine models of future coastal behaviour, especially in a context of sea level rise and climate change.

## Investigate the coastal environment evolution: climatic and morphological cause and a new method for shoreline identification

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*Keywords:* coastal erosion, remote sensing, Sentinel-2, Landsat.

Coastal erosion coupled with human-induced pressure has severely affected the coastal areas of the Mediterranean region in the past and continues to do so with increasing intensity today (Luijendijk et al., 2018). In this context, the Pisa coastal plain shows a long history of erosion, which started at the beginning of the nineteenth century. In this work, shoreline positions derived from historical maps as well as airborne and DGPS (Differential Global Positioning System) surveys were analyzed in a GIS (Geographic Information System) environment to identify the main changes that have occurred in the last 142 years. These analyses were compared with 100 years of discharge data measured at the S. Giovanni alla Vena gauge to identify a possible correlation between the two sets of information. Finally, Sentinel-2 and Landsat images were studied to identify the dispersion of sediments transported by the Arno River. In particular, we found a minimum of fluvial discharge in the years 1954, 1978, and 2012 corresponding to a peak of erosion, while the reduced erosion rate and the fluvial discharge increased in the years 1928–1944, 1954–1975, and after 2012 (Bini et al., 2021). A key topic in the study of the coastal evolution, is the availability of a reliable and quick method of shoreline survey. In this context we would like to identify a new and valid beach topography-based algorithm, able to identify the shoreline. We apply the Structure from Motion (SfM) techniques to reconstruct a high-resolution Digital Elevation Model using a drone for image acquisition. The algorithm is based on the variation of the topographic beach profile caused by the transition from water to sand. The SfM technique is not efficient when applied to reflecting surfaces like sea water resulting in a very irregular and unnatural profile over the sea (Kohv et al., 2017). Taking advantage of this fact, the algorithm searches for the point in the space where a beach profile changes from irregular to regular, causing a transition from water to land. The algorithm is promoted by the release of a QGIS v3.x plugin, which allows the easy application and extraction of other shorelines (Luppichini et al., 2020).

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## **The changing geomorphology of the Volturno delta and coast (northern Campania, Italy): human influence and geological architecture**

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*Keywords:* Volturno, coastline retreat, reclamation, land use changes, subsidence, stratigraphic architecture.

The present geomorphology of the Volturno river delta and related strandplains is largely a product of an intricate long-term relationships between geological evolution and human impacts.

In order to assess the main drivers of the changed landscape in the last 150 years, a multidisciplinary study was carried out by combining historical and geological data. A 150 year cartographic sources were acquired, georeferenced and managed into a GIS environment. Some 1800 well log stratigraphic data were acquired and interpreted to reconstruct the stratigraphic architecture of the plain.

Historical analysis has produced documentary evidence of the geomorphological evolution of the area since the end of the XVII century, when, during the Spanish vice-kingdom, it was subjected to major land reclamation. More than 500 km of canals were built in the coastal area. The development of agriculture and farming on reclaimed land promoted urbanization and increasing landscape fragmentation. The peak was attained between the 1960s and the 1990s, when landscape pattern structure increased in complexity with major alterations of alluvial channels and of the deltaic environment, and retreat of the coastline.

Land use maps were reconstructed for the 1957 and 2012. The overgrowth of the urban areas to the sea, coupled with intensification of agricultural and tourism activities, resulted in the loss of high quality ecosystems such as the humid coastal setting, the lacustrine/marshy back-dune area and, in most cases, also the beach-dune system. The negative sedimentary balance resulting from the reclamation works on the river courses, together with the interventions along the Volturno river basin, resulted in an accelerated and severe coastal erosion. Coastline displacement was calculated at 7 time points, showing timing and causes of trends and rates of variation.

The anthropic impacts were compared with the subsidence trends previously assessed. The lack of an unequivocal correlation of the latter with agricultural land use and zootechnical farm location indicates that these human activities do not exert a significant impact on regional subsidence rates. On the contrary, a net overlay of the subsiding areas with the geological architecture was recognized and in particular with the areal distribution and thickness of deposits such as clayey silts, clays and peats. From geotechnical point of view, these soils can be classified as fine-grained soil (mostly clayey) with poor mechanical properties (high compressibility and low strength). Moreover, the inclusion of significant amount of peat and organic matter clearly reflects high values for the coefficient of secondary compression. The subsidence rates, coupled with the sea level rise due to climatic changes, increase the vulnerability of the coast to erosion, flooding and storm surge and aquifer salinization.

## Reliable calculation of the anthropogenic sediment budget along the Northern Tuscany coast

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*Keywords:* sediment redistribution, coastal erosion, anthropogenic pressure, sediment budget, beach nourishment.

The algebraic sum of sediment inputs, outputs and transfer within a 40 year time interval (1980–2020) represents a study case of a possible way to calculate the anthropogenic sediment budget. This sediment budget is defined as “anthropogenic” because it only involves the interventions related to human activities, which implies that natural inputs (i.d., bedload river discharge) and outputs (i.e., sediment loss to the offshore) are not taken into consideration. A simple and highly replicable methodology to address such a calculation is here described. The methodology has been applied within a littoral cell system along the Northern Tuscany coast (Italy). This area has been selected because it is characterized by either natural and highly urbanized sectors of coast, which are currently subjected to erosion and accretion processes. As in many other coastal settings along the Italian coast, here sediment management affected the sediment budget. The evaluation of this aspect is paramount for a conscious planning of any coastal protection, but it is very hard to quantify in a reliable fashion. Every coastal management policy would be improved should this feature be known.

In the last 40 years, a long series of different protection schemes has been implemented along the Northern Tuscany coast, often financed by a variety of competent authorities (Port Authorities, Municipalities, Marinas, Region). Also for this reason, a dependable accountability of the sediment budget is not possible. In general terms, sediment deposition is concentrated in drift convergent zones or updrift of port structures, which have caused actions such as offshore dumping and sediment disposal into confined facilities: these interventions represent the sediment output in this study. At the same time, bypassing and redistribution processes contributed to the sediment transfer, while the replenishments that have been carried out in the areas most subjected to erosion effects have been considered as sediment input.

Thanks to a thorough collaboration with the main authority of the area, the Region of Tuscany, a detailed assessment of the anthropogenic sediment budget over the last 40 years (1980–2020) has been calculated for the first time. Most coastal protection interventions were carried out to redistribute the sediments from one site to another within the study area (2,949,800 m<sup>3</sup>), while the sediment input (1,011,000 m<sup>3</sup>) almost matched the sediment output (1,254,900 m<sup>3</sup>) in the considered time interval. Summarizing, a negative anthropogenic sediment budget (243,900 m<sup>3</sup>) has been documented.

## Performance of remote sensing algorithms for shoreline mapping under different beach morphodynamic conditions

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*Keywords:* remote sensing, shoreline detection.

Shoreline variability is a key factor in coastal studies. In the last decades, remote sensing techniques have been widely applied and several algorithms for shoreline detection have been developed to extract the so called Satellite Derived Shorelines (SDS). Multispectral and hyperspectral satellites provide images covering large areas with high spatial and temporal resolution, allowing to perform a near real-time analysis of shorelines worldwide. There are several open source algorithms (e.g. SHOREX (Pardo-Pacual et al., 2012) and CoastSat (Vos et al., 2019)) for shoreline detection at sub-pixel level, using freely available multispectral images (Landsat and Sentinel constellations). However, open source applications for SDSs analysis using hyperspectral data are not yet available. Recently the Agenzia Spaziale Italiana (ASI), has launched the PRISMA mission (PREcursoro IperSpettrale della Missione Applicativa), offering medium-spatial (30 m) and high spectral (smaller than 12 nm) resolution.

In this study we present the performance of the CoastSat algorithm applied to multispectral images. Additionally, we show the capability of hyperspectral techniques applied to PRISMA images to detect the shoreline given their higher spectral resolution.

The performance of the CoastSat algorithm was evaluated in two different microtidal beaches of the Italian Adriatic coast (Emilia-Romagna and Marche Regions): Punta Marina (PM) and Sirolo (SIR). The beach at PM is a typical intermediate fine-sandy beach, while SIR is a mixed coarse sand-gravel reflective beach. SDSs were compared to RTK-DGPS surveyed shorelines, measured following the upper limit of the swash zone, and with shorelines derived from a video monitoring station, after manual mapping on variance images. The shoreline derived from in-situ surveys were coincident with Landsat-5, Landsat-7 and Sentinel-2 satellite overpasses. The influence on the identification of SDSs of the run-up extent and beach morphodynamic state was evaluated. The obtained RMSE ranges between ~ 6.5 and 14 m at both sites, indicating that the shoreline is effectively obtained from multispectral images at sub-pixel level. In addition, we analysed the shoreline derived from a PRISMA hyperspectral image of PM. We found that similar results can be obtained using hyperspectral images.

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## The sequential flow of sand through tidal inlet, barrier island, and backbarrier reservoirs

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*Keywords:* barrier islands-tidal inlets systems, sediment dynamics, remote sensing, Merrimack Embayment.

Climate change in New England (USA) is expected to cause an increase in storm frequency and magnitude (Zhang & Colle, 2018). Coupled with sea level rise, intensified storms will increase longshore transport rates and sediment delivery to tidal inlets, which will affect sand bypassing to downdrift shorelines (Lyddon et al., 2019). Greater precipitation will also potentially increase the riverine discharge of sediment at the mouths of estuaries and backbarrier bays and lagoons (Leonardi et al. 2016; Herrling & Winter, 2018).

We have analyzed historical shoreline changes along Castle Neck, one of the five barrier islands within the New England Merrimack Embayment (USA). In addition, we have used remote sensing, hydrodynamic modeling, and grain size trends to predict the formation and migration of shoals and channel shifting in the updrift Plum Island Sound Inlet and downdrift Essex Inlet system (Massachusetts). These analyses allow us to assess the impact of storms on the sediment budget of the beach and sand shoals associated with Plum Island Sound Inlet. In the past 25 years, growth of a large protuberance and sequestration of sand along the mid-Castle Neck shoreline have sand-starved the downdrift shoreline, resulting in a 600-m retreat of the southern spit-end of the barrier. A million cubic meters of sand eroded from the spit washed into Essex Bay causing channel shoaling and migrations. At the same time, spit retreat has increased wave energy inside the inlet impacting valuable shellfish beds and wetlands. Collectively, these studies are aiding in the prediction of how sand will be exchanged among barrier island – tidal inlet reservoirs during a future period of climate change. Our research will help answer questions concerning barrier island shoreline management, inlet channel dredging programs, and beach nourishment practices.

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## **Short-term effects of storm events on the coastline morphology of a Mediterranean microtidal wave-dominated beach (Piscinnì, SW Sardinia)**

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*Keywords:* banquette, videomonitoring system, morphodynamic states, shoreline variability, coastal management.

The Mediterranean coastal areas have been recognized as the most sensitive regions to actual climate and environmental changes. The increased frequency, intensity, spatial extent, duration, and timing of storm events due to climate change can increase the susceptibility of low-lying coastal areas to seawater flooding. The impact of climate change is expected to be strong in areas characterized by severe anthropogenic disturbances. In this context, the understanding of the interaction between beach dynamics, human impact, benthic marine habitat and climate forcing appears crucial for scientists and coastal planners to evaluate coastal risks and to develop the best measures to mitigate them.

This work aims to improve the knowledge of the short-term effects of storm events on the coastline morphology of natural, microtidal, wave dominated beaches located in the western Mediterranean trough the images processing from the data of video monitoring system at Piscinnì beach (SW Sardinia). The morphodynamic states and the spatial shoreline variability of this natural beach has been assessed in our study, during two years of data acquisition, from August 2013 to August 2015 along a 0.3 km stretch of sandy beach. During this period severe storm events mainly related to south-westerly winds (about 50 km/h on average) were happened. For the evaluation of morphodynamic states we carried out forty-two time-exposure (timex) images from three hundred snapshot, with a frequency of 1Hz, of a single recording interval during the storm events, that allow us to understand the morphology of the shoreface (configuration of bars and troughs). For the spatial shoreline variability, we rectified and georeferenced a single snapshot from the day before, during, and two days after the storm event. These images has been loaded in a GIS software where the shoreline was mapped, and the results showed an erosion and a consequent accretion of the studied beach of about 20 m in two days after the event (SW wind and waves) as a result of the deposition of the *Posidonia oceanica* beach-cast litter. Another significant result is the clear reconfiguration of nearshore bars linked to the wave energy flux, calculated by the Copernicus Marine Environment Monitoring Service. A better knowledge of this morphological response induced by storm events is crucial for coastal managers to define beach management plans (for example beach cleaning practice), to prevent coastal risk and to understand the importance of seagrass berm deposition in the formation of natural Mediterranean beaches.

## **Assessing the role of reed and seagrass wracks in coastal protection. An example with numerical modelling integrated with videomonitoring system data in a southern Sardinia beach**

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*Keywords:* reed, seagrass wracks, videomonitoring system, numerical modelling, runup.

This work aims to assess the role played by a beach berm, reinforced by the accumulation of reed and seagrass wracks, on coastal protection against storm-induced floodings. A huge depositional event, mostly consisting of *Arundo donax* reeds from nearby river systems and *Posidonia oceanica* wracks, happened in December 2019 in Poetto beach (southern Sardinia, western Mediterranean). Following the concerns that this event raised among local tourism service providers, the municipal authorities decided to remove the reed wracks. In support of coastal management, a scientific inquiry was commissioned to the Coastal and Marine Geomorphology Group (CMGG), belonging to the Department of Chemical and Geological Sciences of the University of Cagliari (Italy) for the assessment of the berm processes before the removal of the reed wracks. Within the five months between the reed deposition and removal, a video monitoring system collected runup and flooding data during storm wave conditions. These data were integrated by five topographic, three bathymetric and two drone surveys. The presence of the reeds intertwined with seagrass wracks, seems to strengthen the berm, making it more resilient to wave action, eventually offering additional protection against overwash and flooding. These results are supported by a numerical model chain, with the nesting of a phase-resolving model into a phase-averaged model, providing a characterization of wave runup dynamics.

## A low-cost camera for coastal video monitoring

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*Keywords:* coastal video monitoring, low-cost, shoreline.

Video cameras has been widely used in coastal engineering since their first applications in the late Eighties. The main advantages of the video monitoring techniques are a continuous monitoring of the observed region in time, an adequate spatial resolution, and a relatively simple technology to acquire and transfer data. Many studies applied video monitoring techniques to evaluate the shoreline evolution of a littoral (Archetti and Romagnoli, 2011), to reconstruct the intertidal beach or even to extrapolate the whole nearshore (Aarninkhof et al., 2005), thanks to the wave transformation which occurs when waves approach the shore.

However, several limits are still present in the current applications. For instance, video cameras are usually quite expensive, produce a huge amount of data and are not always easily managed in near-real time from remote users. Furthermore, current instrumentation and software are mostly commercial. Here, we present a new tool which uses a Raspberry Pi for the development of a smart camera at very low costs. The software scripts, originally realized in MATLAB (Archetti et al. 2020), are also available in Python and OpenCV for open access implementations. At the current state, the low-cost smart camera (LCC) can acquire images, transfer data, perform on-line rectification and off-line post-processing (e.g., shoreline extrapolation and intertidal bathymetry reconstruction) with a minimum human intervention, which is practically limited to a validation of the results. For coastal video monitoring purposes, next future implementations aim to completely automate on-line analyses, and to implement further scripts (e.g., cBathy, see Holman et al., 2013) on Python. Possible evolutions of the video station include the development of machine learning for several environmental applications.

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## **S16. Extreme environments**

*CONVENERS AND CHAIRPERSONS*

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*Patrizia Fumagalli (University of Milano – Statale)*

*Marcello Natalicchio (University of Torino)*

## Every cold seep tells a story: the case study of Leirdjupet Fault Complex, SW Barents Sea

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*Keywords:* cold seep, Methane, Barents Sea, Habitat, pore water.

Cold seep environments are often associated with chemosynthetic communities at the seafloor, reflecting the spatial distribution and magnitude of methane fluxes in the sediment underneath. Quantifying areal fluxes and rates of consumption via anaerobic oxidation of methane (AOM) is extremely important for better understanding the future response of the benthic filter to climate-induced ocean warming. Short-time-scale transient processes such as tides, seasonal bottom water temperature fluctuations are efficiently recorded in unsteady-state pore water profiles. However, to interpret the long-term trends in methane fluxes and controlling factors one needs to integrate this data with sedimentary proxies and conduct paleo-reconstructions. We present a case study from the SW Barents Sea at Leirdjupet Fault Complex, where active methane seepage has been observed in summer 2018 from 295 m to 350 m water depth and is associated with microbial mats and tubeworms. We discuss the modern seepage conditions based on pore water data and habitat maps generated through Object-Based Image Analysis (OBIA) classification, and discuss the history of seepage recorded in sediment cores. A new ROV survey conducted in June 2021 in the same area revealed a very different situation compared to 2018, consistent with the long-term reconstructions since Late Weichselian deglaciation.

## Linking plate tectonic settings and microbial functions on a global scale

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*Keywords:* biosphere, geosphere, plate tectonics, transition metals.

Microbial communities carry out the core redox reactions that control biogeochemical cycles of elements and nutrients mainly thanks to enzymes that use transition metals as catalytic cofactors, suggesting a direct link with the environmental availability of those metals. As Earth’s biosphere and geosphere have coevolved over time, the availability of these metals has changed, influencing surface redox conditions as well as cycling of elements and volatiles, leading to new and more abundant reductant-oxidant pairs, probably impacting the evolution and distribution of metabolic processes and expanding the network of microbial metabolism. Electron transfer reactions are the common thread of the history of life from the very beginning, and the emergence of proteins capable of incorporating metals that facilitate redox reactions is the foundation of the strong link between biosphere and geosphere.

The delivery of life’s relevant transition metals is controlled to a first order by tectonic processes. We present here geochemical and microbiological coupled analysis of data from over 250 geothermal locations globally. Our work aims to look for links between the delivery of biologically important transition metals to the surface through plate tectonics and microbial functional diversity.

Our dataset reveals correlations between key microbial functions and differences in the delivery of the key metal cofactors to the surface of our planet. Understanding which processes determine the delivery of biologically important transition metals, and how these affect the distribution of microbial enzymes critical for biogeochemistry, will allow to shed light on the interaction between Earth’s geosphere and biosphere, opening new doors not only on better understanding our planet, but also on what are the characteristics to look for in a planet potentially suitable for life.

## **Deeply-sourced springs microbial diversity: a window into the deep of the Earth**

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*Keywords:* subduction, hot springs, backarc, biogeochemical cycles, microbial diversity.

Subduction zones are critically involved in recycling of volatiles and elements between the surface and planetary interior and play a key role in climate stability and planetary habitability. Both in the forearc and backarc regions the lithosphere is affected by the deformation induced by the plate movements, generally favouring lithosphere fractures formations and the widespread origination of deeply-sourced springs, hot or cold, that carry deep fluids and gases up to the surface. These fluids and gases originate from the subducting slab as well as from the interaction of the rising fluids and melting with the overlying crust, and generate “hot spots” of microbial diversity and activity driven by the sharp redox, geochemical and often thermal gradients. Given their direct connection with the subsurface, deeply-sourced springs can be used as a window into the deep to understand processes happening at depth. To be able to use deeply-sourced springs as conduits to the subsurface we need to be able to deconvolve the surface signals from the deep subsurface ones. Despite the abundance of studies looking at the microbiology of hot springs globally, there are relatively few studies linking microbial diversity to the underlying geological processes, and especially in the backarc regions information are scarce. Here we present data on the microbial diversity of the deeply sourced springs along the backarc of the volcanic complex of Puna, Argentina, and assess the extent of influence from surface processes of the spring communities. We conclude that surrounding soil and shallow subsurface microbial communities minimally contribute to the diversity of the deeply sourced fluids that thus represent key samples to investigate the deep continental subsurface.

## **Anatomy of a sulfur-bearing carbonate concretion (Late Miocene, Northern Italy): evidence of pulsating methane flows associated with the formation and destabilization of gas hydrates.**

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**Keywords:** gas hydrates, sulfur, microorganisms, Miocene.

Gas hydrates (GH) are ubiquitous features of modern continental margins but in the geological past their evidence is elusive and mostly represented by carbonate concretions of various shape and size (clathrites). The precipitation of carbonate minerals is induced by anaerobic oxidation of methane (AOM) at the sulfate-methane transition zone (SMTZ), that is performed by a consortium of microorganisms including methanotrophic archaea and sulfate reducing bacteria. As their modern counterparts, ancient clathrites show distinctive petrographic (bubble fabric, brecciation etc.) and geochemical features that testifies the formation and destabilization of GH in the subsurface. Gypsum and native sulfur are rarely described as authigenic minerals associated with GH. When found, these minerals are thought to reflect vertical oscillation of the SMTZ, in turn controlled by GH formation and destabilization. Here we investigate a five meter-sized, sulfur-bearing carbonate concretion hosted in lower Messinian fine-grained slope deposits from NW Italy. The internal texture of the concretion consists of: i) wrinkled laminae composed of alternating clotted micrite and filamentous microfossils corresponding to sulfide-oxidizing bacteria like *Beggiatoa* and *Thioploca*. The laminated microfacies is brecciated and clasts are rimmed by an isopachous aragonite cement; ii) irregular-shaped cavities partially filled with calcite. The strongly negative  $\delta^{13}\text{C}$  values (up to  $-50\%$  PDB) of the carbonate cements confirm that AOM was the driving process responsible for carbonate precipitation. The vacuolar and brecciated texture are similar features of modern clathrites; moreover, the positive  $\delta^{18}\text{O}$  values (up to  $5\%$  PDB) suggest that methane was sourced by GH destabilization. Interestingly, sulfur is found in cm to dm-sized flames parallel to bedding and irregular nodules. Sulfur shows a bright autofluorescence, suggesting high contents of organic matter and is typified by filamentous objects 3-4 micron across, of putative microbial origin. We suggest that the sulfur-bearing carbonates formed at an ancient SMTZ in the shallow subsurface, associated with the formation of gas hydrate. Sulfur is most likely the product of the oxidation of residual sulfide, due to vertical displacement of the SMTZ following destabilization of GH. The laminated texture still preserved in some portion of the concretions reflect instead the seepage of methane-rich fluids at the seafloor and its colonization by dense microbial mats dominated by sulfide oxidizing bacteria. The absence of metazoans possibly reflects high flux of sulfide and / or low oxygen conditions at the seafloor. The studied carbonate concretion is the solid evidence of pulsating methane flows associated to the formation and destabilization of gas hydrates in the shallow subsurface and the consequent expulsion of methane-rich fluids at the seafloor.

## **Geosphere and Biosphere co-evolution through space and time**

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*Keywords:* geosphere-biosphere coevolution, biological processes, Earth evolutionary trajectory and habitability.

A complex set of feedback mechanisms has allowed our planet to stay habitable for most of its 4.5 billion years of evolutionary history. During this time, life has significantly influenced the surface redox state of our planet, impacting the diversity of minerals available, the planet's atmospheric composition and long term climate stability. While the coevolution of the geosphere and biosphere has been recognized for some time for some events and processes (for example the Great Oxidation Event), the extent and diversity of coupled life-planet processes remains unclear. In this talk I'll review the current knowledge regarding geosphere-biosphere coevolution, highlighting biological processes that have a significant planetary scale impact and might have played a key role in influencing Earth evolutionary trajectory and habitability.

## **Paleoecological reconstruction and modern analogues from foraminiferal proxies in the Middle Branch of Bue Marino Cave (Sardinia, Italy). Work in progress**

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**Keywords:** marine caves, Mediterranean Sea, sediment texture, benthic foraminifera, ecological indicators, climate record.

Being at the boundary between marine and continental realms, marine caves are affected by wide environmental variability for the interaction of marine and continental waters; for this, they are natural laboratories for studying the effects of seasonal and long-term environmental variability also in the perspective of global changes. The first studies of benthic foraminifera from marine caves of the Mediterranean Sea have been carried out in the Gulf of Orosei in the context of a scientific project which started in 2014 and has continued to this day. They demonstrated that benthic foraminifera are very sensitive environmental proxies in these habitats, due to their high diversity and adaptability. The Bue Marino system is constituted by North, Middle and South Branch which join together close to the coast. The study of benthic foraminifera and sediment texture from surface samples, associated with parameters of bottom water, indicated that the Middle Branch was characterized by warmer, saltier and less oxygenated water than the rest of the cave, and by finer sediment with abundant vegetal debris, probably supplied from the mainland during strongly rainy periods (Romano et al., 2021). Then, it was reasonable hypothesizing that cave sediments, although deposited in enclosed environment, are reliable archives of past climatic changes.

A 18 cm long sediment core, collected in 2018 in the Middle Branch, was studied for grain size and benthic foraminifera in order to highlight evidence of temporal changes of environmental conditions and their causes. In the whole core, sediment texture was homogeneous, with prevailing sand and silt in similar proportions, while clay was less abundant and gravel nearly absent. Two hyaline (*Ammonia inflata* and *A. tepida*) and one agglutinated species (*Eggerelloides advenus*), dominated the assemblage, accounting for a total of 70-92%. A main change occurred along the core, at 11 cm depth, for the shift from an assemblage in the lower section with prevailing *A. inflata*, to another one where the highly opportunistic *E. advenus* and *A. tepida* dominated. Of these two assemblages, the latter was more similar to that recorded in the surface sample (0-2 cm), collected at the same sampling station, for the dominance of *E. advenus*, despite *A. inflata* slightly prevailed on *A. tepida*. It was interpreted as the result of a highly organically-enriched environment where opportunistic taxa benefited of abundant degraded organic material under low-oxygen conditions. The prevalence of the “indifferent” *A. inflata* in the lower core suggests less stressed conditions with minor supply of continental vegetal debris, probably due to less frequent and/or intense rainy episodes in past times.

Romano E., Bergamin L., Di Bella L., Frezza V., Pierfranceschi G., Marassich A. & Provenzani C. 2021. Benthic foraminifera as environmental indicators in extreme environments: The marine cave of Bue Marino (Sardinia, Italy). *Ecol. Indic.*, 120, 106977.



## **Crypts in porous basanite: Extreme environments hosting fungal-bacterial micro-ecosystems in a deep-sea volcano, Vesteris Seamount, Greenland Sea**

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*Keywords:* Cryptoendoliths, Basanite, Fungal-bacterial interaction, Extreme environments.

Microbes colonize some of Earth's most extreme environments, sometimes providing refuges for symbionts and decomposers. The vesicles in porous basalt and basanite of deep-sea volcanoes support flourishing subsurface micro-ecosystems, which are part of the deep biosphere of the igneous oceanic crust. Despite the abundance and antiquity of cryptoendoliths in structural cavities of the oceanic crust, the evolution and ecology of these cryptic ecosystems remain mostly elusive. Here we report morphological and geochemical properties of microbial body fossils in rock samples collected from Vesteris Seamount during cruise MSM86 of MS Maria S. Merian in 2019. The highly porous basanites exhibit densely intergrown filamentous networks and laminated deposits on vesicle walls of probable biotic origin preserved as secondary minerals like manganese- or iron-oxides and others. Morphological evidence suggests the dominance of fungi among filamentous fossils, whereas basal coatings on internal vesicle walls resembling minute stromatolites are interpreted as remains of iron- or manganese-oxidizing chemolithoautotrophic bacteria. Hand samples, thin sections, and polished slabs of vesicular basanite also yielded *in vivo* fungal mycelia associated with globular, botryoidal, and dendritic stromatolites. The spatial relation and growth of fungal filaments upon a basal microbialite suggests a symbiotic-like relation of the supposedly autotrophic bacteria and the heterotrophic fungi. Such association would explain the recent findings of a vital fungi community in the oceanic lithosphere.

## Neogene seepage carbonate deposition in the Crotona Basin (South Italy), preliminary results

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*Keywords:* cold seep carbonate, extreme environments, chemosynthetic communities, Calabria.

A large Neogenic “Calcarei a Lucina” deposit - i.e. hydrocarbons-rich cold seep carbonate -, reaching 40 m of thickness and several tens of meters of extension, crops out in the Crotona Basin (South Italy). It is composed of authigenic carbonate forming a facies referable to the conduits of gas/fluid, crosscutting early carbonate-cemented bioclastic and siliciclastic sediments definable as pavement facies.

Conduits are commonly characterized by the accretion of meters thick thinly laminated and banded calcite and formed by the alternation of dark micritic laminae and clear crystalline layers. The micritic laminae are characterized by an autochthonous microbial peloidal to dendrolitic fabric, incorporating coprolites and planktonic foraminifera. In contrast the crystalline layers are characterized by microspar laminae and centimeters thick sparry crusts composed of prismatic zoned calcite crystals.

The pavement facies is typified by foraminiferal bioturbated mudstone/wackestone gradually passing to mixed arenites as the increasing of the siliciclastic grains composed of quartz, plagioclase, phyllosilicates, aphanitic lithic grains, phaneritic rock fragments, and heavy minerals, all immersed into a micritic carbonate matrix, and indicating both sedimentary and crystalline basement source. The foraminiferal assemblage, characterized by almost exclusively by planktonic forms, and the relative proportion of sandy/silty grains, indicate a deep-water setting with occasional siliciclastic coarser sedimentary flows.

A common chemosynthetic macrofauna composed of often articulated and in life-position Lucinids, Mytilids and Vesicomids bivalves, associated to tubeworms and gastropods, is commonly present into such sediments.

The deposits of the pavement facies are commonly brecciated, possibly because the overpressure conditions established by the gas/fluid injection, and the displacive growth of the conduit deposits that crosscut the sediments, suggesting a very early cementation of the micritic matrix. Clasts of breccias are also later lined by primary fibrous to acicular isopachous to fan-shaped calcite cement.

The high diversity of the heavy minerals in the mixed arenite deposits together with the presence of unstable (green amphibole) and moderately stable (epidote, garnet, sillimanite) heavy detrital species, indicates a burial depth comprised between 600 m and 2000 m during which a late diagenetic phase occurred. A pervasive neomorphic recrystallization of the carbonate grains and the precipitation of mosaic equant calcite cements, filling the remnant voids, took place during this phase.

**S17.**

**Carbonate rocks: from sedimentation to diagenesis**

*CONVENERS AND CHAIRPERSONS*

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## **Facies architecture and diagenesis in a Mississippian mud mound complex from Derbyshire (UK)**

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The Mississippian Derbyshire Carbonate Platform outcrops, in the Peak District in UK, host many mud mound complexes (Gutteridge, 1995). The one near the village of Monyash, in Ricklow Quarry, is one of the best for outcrop quality and accessibility. Fieldwork and petrographic study allowed recognising three facies associations in the complex. A basal tabular portion, five metres thick, consists of nodular packstone-rudstone beds with patches of clotted peloidal-leiolitic micrite boundstone, interbedded with tabular clotted peloidal-leiolitic micrite/fenestellid bryozoan boundstone mounds (FA 1). The overlying, dome-shaped, decametre-size mound complex core formed by lateral accretion of numerous dome-shaped, metre-size mounds. These consist of an association of fenestellid bryozoan/clotted peloidal-leiolitic micrite boundstone with radiaxial fibrous calcite cement (FA 2). The mound core is flanked by dipping beds characterized by clotted peloidal-leiolitic micrite/fenestellid bryozoan boundstone, passing downslope to skeletal packstone with brachiopods and crinoids (FA 3). Flank beds are transitional to the crinoid-rich packstone/grainstone-rudstone beds occurring laterally to the mound complex. Clotted peloidal-leiolitic micrite textures have been interpreted as originated from in-situ precipitation mediated by the presence of microbial mats on the sea floor (Pickard, 1996). Likely, the complex developed during a deepening of the depositional environment in a middle-ramp intraplatform setting, by microbial communities colonisation of the seafloor. Microbially-mediated in-situ precipitates were then occupied by brachiopods and bryozoans, forming mounds whose vertical growth was prevented by currents (FA 1). A further deepening of the environment allowed vertical growth and coalescence of dome-shaped mounds, which accreted to form the decametre-size core (FA 2). Flank beds (FA 3) developed as a result of the metre-scale mound complex core relief over the seafloor. The presence of inner ramp crinoidal grainstone beds onlapping the complex core and vadose cements on top of the mound complex reveal that mound growth was interrupted by a phase of relative sea-level fall and subaerial exposure. Preliminary evaluation of the diagenetic history through petrographic analysis shows a first phase of marine diagenesis (radiaxial fibrous calcite cement), followed by meteoric diagenesis (dissolution vugs, pendant vadose cement). During the following burial phase, mechanical compaction, cementation (blocky calcite cement), silicification and pressure solution occurred. Fissure formation was followed by precipitation of coarse late calcite cement. Finally, hydrocarbons and mineralising fluids pumped from adjacent basinal areas (e.g. Walkden & Williams, 1991) opened fractures, stylolites and intercrystalline discontinuities. Presence of bitumen in the resulting fissures prevented the precipitation of further calcite cement, leaving open secondary porosity.

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## Using hydrothermal dolomite to constrain the age and genesis of Alpine-type Pb-Zn deposits. Insights from the Gorno district (Lombardy, Italy)

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*Keywords:* ore deposits, hydrothermal, sedimentary basins.

Hydrothermal dolostones are often associated with Mississippi Valley-type (MVT) ore deposits. Both are of major economic importance and are genetically related to hydrothermal fluid flow through large volumes of rock. The difficulty to constrain the spatio-temporal relationships of dolomitization and mineralization has generated controversy concerning the corresponding ages and burial depths. This has led to the proliferation of interpretive models of both dolomitization and ore mineral precipitation. The data presented here are part of a larger study of the well-known Gorno mining district in Lombardy (N Italy), which is a classic example of the Alpine-type MVT deposits, characterized by complex Pb-Zn-Ag ( $\pm$  fluorite  $\pm$  barite) mineralization. Little radiometric age data are currently available for the Alpine-type deposits (Henjes-Kunst et al., 2017). Consequently, their genesis is still debated. The Gorno orebodies are strata-bound and developed in the Lower Carnian stratigraphic succession of the central Southern Alps. Replacive and void-filling saddle dolomite and calcite cements are intimately associated with the sulfides, and their precipitation occurred alternately during the same mineralizing event. In situ U-Pb isotope analyses were performed on the ore-related carbonates, revealing ages ranging between  $229.9 \pm 11.2$  Ma and  $227.1 \pm 17.9$  Ma, which broadly overlap the depositional ages of the host rocks. These data represent the first radiometric ages for the district, indicating early mineral deposition in a relatively shallow burial setting. Microthermometry conducted on primary fluid inclusions in saddle dolomite crystals yielded homogenization temperatures of  $\sim 80$  to  $130$  °C. These temperatures are significantly higher than that of the host rocks at shallow burial, and thus document the occurrence of hydrothermal circulation *sensu stricto*. The presented data provide new insights into the conditions of sulfide-ore precipitation in the Gorno district and, more widely, in the Alpine-type deposits, placing the large-scale mineralizing event into an extensional setting prior to the Early Jurassic western Tethys rifting phase. Early diagenetic formation and the association with extensional tectonics are also common features of the Irish-type Zn-Pb deposits. This similarity between Alpine and Irish-type deposits raises a classification problem. The term MVT commonly has a genetic connotation, implying an epigenetic origin. However, the minimum age difference between host rocks and mineralization is not always sufficiently clear to properly use the term “epigenetic”. Thus, we suggest a more general use of the term MVT, encompassing both late-diagenetic/deep burial and early-diagenetic/shallow burial deposits.

Henjes-Kunst E., Raith J.G. & Boyce A.J. (2017) - Micro-scale sulfur isotope and chemical variations in sphalerite from the Bleiberg Pb-Zn deposit, Eastern Alps, Austria. *Ore Geol. Rev.*, 90, 52–62.

## **Biological induced mineralization of early carbonate cements in an Anisian microbial buildup (Basilicata, Southern Italy)**

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*Keywords:* early cements, organic matter, biomineralization, fossil record.

The research on mineral nucleation, controlled, induced or influenced by organic molecules, is in continuous evolution and the finding of new bio-products are fundamental in geobiological studies. Here we discuss the role of organic compounds in the deposition of early cements in an Anisian buildup, suggesting to consider them as the product of unconventional biomineralizations. The term unconventional is utilized to discriminate these carbonate components from skeletons and microbialites, which are related to well-known biotic mineralization processes and thus considered as conventional biomineralizations processes.

In the studied buildup, microbialites and microencrusts represent the main building components of the carbonate boundstone, while diffuse early cements deposited in the microcavities and among the grains contribute to strengthen the framework (Guido et al., 2021). These isopachous early cements show alternance of cloudy and whitish bands, often resembling microstromatolite textures. During their growth, organic matter remains were trapped only within the crystals forming the cloudy bands, as well as in the autochthonous micrite that form the microbialite texture. In particular, the studied Anisian early cements show the alternance between phases of biologically induced/influenced growth (cloudy bands) and phases of abiotic growth (whitish bands) that are in line with the mineralization model proposed for early cements forming in recent beachrocks (Webb et al., 1999).

The mutual approach with epifluorescence and Raman spectroscopy allows to prove the key role of biological processes in the deposition of the early cements. Even if further investigation, with characterization of the biomarker in GC-MS, are necessary to elucidate the specific biogeochemical pathways involved of the mineralization, the present research supports the possible use of early cements as a new tool to detect and investigate biological signature in the fossil record.

Guido A., Palladino G., Sposato M., Russo F., Prosser G., Bentivenga M. & Mastandrea A. (2021) - Reconstruction of tectonically disrupted carbonates through quantitative microfacies analyses: an example from the Middle Triassic of Southern Italy. *Facies*, <https://doi.org/10.1007/s10347-021-00631-2>.

Webb G.E., Jell J.S. & Baker J.C. (1999) - Cryptic intertidal microbialites in beachrock, Heron Island, Great Barrier Reef: implications for the origin of microcrystalline beachrock cement. *Sediment. Geol.*, 126, 317-334.

## **Facies analysis and paleoenvironmental evolution of the Norian-Jurassic sedimentary successions of the Northern Calcareous Alps (Stumpfmauer-Austria)**

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*Keywords:* Climatic and environmental changes, Western Tethys, Norian-Jurassic sedimentary succession.

In Late Triassic-Early Jurassic time, across one of the major extinction event of the Phanerozoic, the Western Tethys was affected by climatic and environmental changes followed by extensional tectonics related to the opening of the Alpine Tethys. The Norian-Upper Jurassic successions of the eastern Northern Calcareous Alps (Stumpfmauer, Austria), exposed in the Königsberg and Oisberg synclines show the transition from the early dolomitized peritidal facies of the Norian Hauptdolomit to the Rhaetian limestone-siliciclastic succession of the Kössen Formation.

34 facies have been characterized in the succession, composing eight distinct superimposed sedimentary units labelled from A to H, from base to top. Peritidal facies organized in shallowing-upward cycles capped by subaerial exposure and overlain by claystone beds characterize Unit A. Unit B is associated with fossiliferous claystone and marlstone attesting for open marine subtidal conditions developed below the effective wave base. The frequent siliciclastic input affecting Unit B records a shift from arid to humid climatic conditions. Unit C facies association defines a continuous coral limestone bed representing a regional marker developed in a low-energy setting with reduced siliciclastic input. Unit D, marking a renewed clay input, is characterized by skeletal peloidal packstone/wackestone and coated-grain grainstone forming subtidal shallowing-upward cycles capped by subaerial exposures, representative of open marine subtidal conditions affected by high-frequency sea-level changes. Unit E starts with a basal transgressive lag with crinoidal lithoclastic rudstone overlain by progradational cross-bedded coated grain-oidal grainstone with quartz, developed in a high-energy inner ramp setting: The disappearance of bioclasts suggests that this unit may reflect the T-J biotic crisis. A sharp change in deposition characterizes Unit F with bivalve and ostracod wackestone/floatstone overlain by microbial boundstone with *Cayeuxia* associated with peloidal packstone/grainstone. This facies association is indicative of low-energy deep water conditions passing toward the top to shallow-water setting with moderate energy conditions related to subtidal lagoonal environments. Unit G consists of cross-laminated crinoidal coated grain grainstone and spiculite developed in a relatively deep-water shelf setting affected by detrital quartz siliciclastic input. Unit H records the definitive drowning of the shelf: it consists of red crinoidal, thin-shelled bivalves packstone/rudstone with cephalopods and radiolaria wackestone attesting for a deep pelagic environment.

The observed stratigraphic setting can be framed in the regional evolution of the Western Tethys and can be traced from the Western Carpathians to Southern Alps suggesting coherent environmental changes and stratigraphic evolution, documenting the role played by climate and tectonics on sedimentation at regional scale.



## **Climatic and sea-level changes control travertine deposition: the *Lapis Tiburtinus* case study (Tivoli, Central Italy)**

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*Keywords:* travertine, Pleistocene, Lapis Tiburtinus, Central Italy, climate changes, base level fluctuations.

Several Neogene-Quaternary basins in central-western Italy host travertine deposits and are influenced by extensional and strike-slip tectonic activity. These continental carbonate deposits are principally related to hydrothermal fluids circulating and emerging onto the surface along fractured carbonate bedrocks or discontinuities. The Acque Albule Basin (Tivoli, Central Italy) is a tectonically-controlled depression hosting the Pleistocene Lapis Tiburtinus travertine.

The 3D modelling permits to reconstruct the geometry and architecture of the geobodies filling the sedimentary basin and its evolution. The reconstruction of the different surfaces bounding the travertine geobodies of the Lapis Tiburtinus highlights a complex scenario mainly characterized by depression and relief morphological elements, associated with subaqueous, palustrine, slope and channel depositional environments.

The results obtained by the 3D modelling of the quarried area of the Lapis Tiburtinus travertine deposits and the spatial distribution of discontinuity surfaces and geobody architectures provide information on the factors influencing the sedimentary filling of the Acque Albule Basin.

The presence of E-W oriented lens-shaped geometries laterally migrating reveals a drainage system persistent through time toward the southern part of the study area in the direction of the Aniene River, bordering the Acque Albule Basin in the South.

The travertine deposits related to the Lapis Tiburtinus developed in an area of 28 km<sup>2</sup> and accumulated in a system of sub-basins, each 1-2 km<sup>2</sup> wide, mainly characterized by subaqueous conditions and interconnected by a hydrographic network related to the Aniene River.

The results obtained reveal that tectonic activity was the main control on the evolution of the Acque Albule Basin over a time-scale of hundreds of thousands to million years, influencing the basinal subsidence through time and the locations of active hydrothermal springs precipitating the travertine.

However, climatic changes govern rainfall precipitation rates and groundwater level affecting spring discharge and travertine deposition rate.

Glacio-eustatic oscillations linked to the climatic fluctuations of the last 115 kyrs controlling the Aniene River base level have influenced the depositional setting and the geometry and architecture of travertine geobodies.

## Maximum and minimum depositional age models in lacustrine systems from jointly applied zircon and carbonate U-Pb geochronology (Yacoraite Fm., Maastrichtian-Danian, Argentina)

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*Keywords:* U-Pb geochronology, ash layers, carbonates, lacustrine deposits, depositional age model, sedimentation rate.

The Yacoraite Fm. (Salta rift, Argentina) consists of Maastrichtian-Danian lacustrine carbonate and siliciclastic deposits interbedded with volcanic ash layers and organized in four third-order stratigraphic sequences. It offers the exceptional opportunity to jointly apply zircon and carbonate U-Pb (LA-ICPMS) geochronology resulting in a Maximum Depositional Age depth model (MDA, from zircon grains) together with an unprecedented Minimum Depositional Age depth model (MIDA, from carbonates). MDA from 10 ash layers were linearly interpolated to derive an MDA depth model. MIDA were determined for 19 carbonate phases including microbialite, ooids, oncoids and early lacustrine cements of calcitic and dolomitic mineralogy. Weighted average ages (MIDAw) were defined from different carbonate phases belonging to the same sample to build a MIDA depth model. Sedimentation rates were calculated from both MDA and MIDA depth models between pairs of dated samples and used to estimate the age of key stratigraphic surfaces such as sequence boundaries, as well as the duration of the four stratigraphic sequences.

MDA and MIDA from ash layer and carbonate samples get younger upsection and are included between  $67.24 \pm 0.94$  and  $63.33 \pm 0.56$  Ma, and between  $66.50 \pm 0.98$  and  $63.10 \pm 0.89$  Ma, respectively, which agree with biostratigraphic constraints. The MDA and MIDA depth models are remarkably consistent and reveal a sedimentation time window for the Yacoraite Fm. of  $67.70 \pm 0.94$  Ma to  $62.30 \pm 0.56$  Ma (duration  $5.30 \pm 1.50$  Ma) and of  $67.29 \pm 1.86$  Ma to  $61.84 \pm 1.00$  Ma (duration  $5.30 \pm 2.40$  Ma), respectively.

Results from this study demonstrate that in situ carbonate U-Pb dating combined with a diagenetic analysis represents a valuable chronostratigraphic tool to estimate sedimentation rate and duration in poorly time-framed depositional systems.

## **The continental bridge between Africa and Adria: new insights from the Lower Cretaceous of NW Sicily (Italy)**

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*Keywords:* Cretaceous, Theropoda, Urganian, palaeogeography, biostratigraphy, Carbonates.

Classic paleogeographic scenarios for the Cretaceous of the Central Mediterranean area depicted the peri-Adriatic region as punctuated by patchy carbonate platforms far from the main emergent lands. The increasing dinosaur record of African affinity in Italy questioned such palaeogeographic scenarios and suggests the proximity of landmass areas connecting Africa and Adria during Cretaceous times. Besides several track-sites and some exceptionally-preserved specimens, the Italian dinosaur record also consists of isolated bones, among which the fragment of a theropod bone discovered in NW Sicily (Capaci) in a carbonate succession pertaining to the Panormide Carbonate Platform (PCP). This bone fragment was previously referred to the Cenomanian and its occurrence strongly supports the hypothesis of a land bridge connecting Africa and Adria via PCP. More recently, new sedimentological and biostratigraphic data from this carbonate succession (i.e. Pizzo Muletta) have allowed to predate the chronostratigraphic position of the dinosaur bone to upper Aptian–lower Albian and to assess a detailed Aptian–Cenomanian evolution of this sector of the PCP. In particular, a karstic overprint has been observed thus indicating a subaerial exposure of the platform preceding its drowning in latest Cenomanian times. The obtained results extend the chronostratigraphic interval of the possible land bridge between Africa and Adria at least from Aptian to Cenomanian and highlight the progressive tectonic dismantling of this connection during the Late Cretaceous.

## **Palaeoecology of late Triassic bioconstructions in the Western Tethyan domain (M.te Cocuzzo - North Calabria)**

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*Keywords:* Triassic, Tethys, Calabria, patch reef, palaeoecology.

The Monte Cocuzzo tectonic window, located in the central part of the Catena Costiera Calabria (Calabria - south Italy), hosts a thick Norian-Rhaetian carbonate succession characterized by three different depositional units representing three successive carbonate platform systems of the western Tethys realm: early-middle Norian Lower Complex, middle-late Norian Intermediate Complex and late Norian-Rhaetian Upper Complex. The Lower Complex platform system is characterized by spread and isolated bio-constructed bodies showing an oligotypic community with a primary framework composed by sponges, red algae and corals; and a secondary framework by microbialites, foraminifera and serpulids. Globose clusters of sponges (Olangoceliidae), encrusting red algae (Solenopora) and microbial crusts, represent the start-phase of the reef construction. In the successive frame-building phase, sponges and red algae progressively decrease in favor of pennulate isolate (*Distichophyllia* sp.) and colonial (*Retiophyllia* sp.) corals, the latter forming dendroid fun-shaped tufts (50-60 cm thick). Coral skeletons are encrusted by microbial laminae, serpulids and red algae and are immersed into bioclastic detritus composed by echinoid fragments, bivalves and gastropods tests and rare bryozoans. The primary framework is composed by 41% sponges, 35% red algae and 24% corals, whereas the secondary framework by 41% foraminifera, 35% microbialites and 24% serpulids. The accessory organisms are 19% echinoids, 8% bivalves and 6% gastropods and the rest of the volume is represented by non-bioclastic sediments (39%) and primary cements (28%). The bioconstructions are commonly overlapped by bioclastic packstone-grainstones enriched into dasycladacean algae and foraminifera indicating a relatively shallow water environment, probably characterized by disphotic and eutrophic waters as testified by the presence of pennulate corals. These bioconstructions can represent patch reefs located along the carbonate platform margins directly facing an internal restricted basin generally characterized by stressed environmental conditions. In fact, during the whole Norian, syn-depositional down-faulting pulses, accompanied by gradual eustatic sea-level drops, induced repeated episodes of basin restrictions with a consequent limited water circulation and stressed conditions affecting the late Triassic Western Tethyan general carbonate platform domain.

## **The Messinian pre-salt carbonate/evaporite platform system of the Central Mediterranean (Calcare di Base Fm - North Calabria)**

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*Keywords:* Calcare di Base, evaporites, Messinian Salinity Crisis, microbial carbonates, pre-salt.

The Calcare di Base (CdB) Fm is a carbonate/evaporitic unit formed during the onset of the Messinian Salinity Crisis in the the central Mediterranean region, before the deposition of massive halite and sulphate bodies.

An integrated facies and stratigraphic analysis of the CdB was performed along the neogenic basins of north Calabria, that allowed to propose a sedimentary and evolutionary model in which the CdB consists of a carbonate, with minor evaporites, platform-to-slope system, formed during a general cold and arid climate period, characterized by precession-forced more humid intervals.

The inner platform setting was generally characterized by a sabkha-type environment with scattered lakes and coastal lagoons grading into a shallow-marine unrimmed shelf. In particular, as the general aridity, restricted conditions frequently established, inducing hypersalinity and local anoxia. Such general stressed environmental conditions favored the thriving of extensive lithifying microbial-mats dominated by sulfur bacteria, that acted as the main carbonate factory along the whole shelf, producing widespread microbial carbonate deposits, associated with precipitation of gypsum-dominated evaporitic deposits. During the more humid periods an increasing in the runoff provoked the substantial reduction of the carbonate production, the interruption of the evaporitic sedimentation, the input of fine to coarse silicilastic sediments, and the formation of dissolution breccias.

The slope setting is inferred with a general low-angle profile and was typified by breccias and disorganized floatbreccias commonly developing along the inner slope, and by slides, slumps and channelized turbidites forming along the mid-to-outer slope to basin. During the arid periods the resedimentation processes were generally limited and characterized by monomictic (carbonate) debrites. In comparison, during the humid phases, the enhanced erosion and the consequent mixed carbonate/evaporite/terrigenous sediment exportation towards the basin, resulted in the formation of thicker polymictic breccia and megabreccia bodies.

**S18.**  
**Geology and ecosystems**

*CONVENERS AND CHAIRPERSONS*

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*Alessandra Savini (University of Milano Bicocca)*

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## ***Chondrodonta* (Bivalvia) proliferation in Cretaceous peri-Adriatic shallow-water carbonates: a comparative study**

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**Keywords:** *Chondrodonta*, OAE1a, OAE2, Apulia Carbonate Platform, Adriatic Carbonate Platform.

*Chondrodonta* is an epifaunal, filter-feeding, oyster-like bivalve commonly reported in worldwide Barremian – Turonian shallow-water limestones. It shows a particularly high concentration and a predominance over other biota in specific stratigraphic intervals straddling the Cretaceous Oceanic Anoxic Events 1a and 2. However, a precise timing between the flourishing of *Chondrodonta* and the interval of OAEs has yet to be established and the environmental changes possibly triggering its proliferation still need to be understood. In this work, a comparison of sedimentologic, taphonomic and geochemical signatures between lower Aptian and upper Cenomanian *Chondrodonta* accumulation of the peri-Adriatic area is presented.

The lower Aptian *Chondrodonta* accumulations are exposed on the Gargano Promontory (southern Italy) within the inner platform facies of the San Giovanni Rotondo Limestone (Apulia Carbonate Platform). *Chondrodonta* appears within requieniid rudist limestones and reaches a brief phase of maximum proliferation in monospecific biostromes, correlated right below the negative  $\delta^{13}\text{C}$  excursion marking the onset of OAE1a. Increasing nutrient load and low-energy, restricted seawaters with fluctuating oxygenation, allowed *Chondrodonta* to proliferate and to outpace the less tolerant rudists at the dawn of the anoxic event.

The upper Cenomanian *Chondrodonta* accumulations are exposed on the Istrian Peninsula (northwestern Croatia) within the inner platform facies of the Milna Formation (Adriatic Carbonate Platform). *Chondrodonta* appears within radiolitid rudist limestones and reaches a phase of maximum proliferation in quasi- to monospecific biostromes, correlated below the onset of OAE2. Increasing nutrient load, intermittent terrigenous inputs, fluctuating oxygenation and circulation, represented environmental stressors that allowed *Chondrodonta* to become the dominant macrobenthos and to prevail over rudists at the prelude of the anoxic event.



## Late Miocene-early Pliocene Biogenic Bloom: a Tasman Sea perspective

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**Keywords:** Late Miocene, biogenic bloom, benthic foraminifera, stable isotope, paleoproductivity, IODP.

The late Miocene-early Pliocene Biogenic Bloom was a period of enhanced marine biological productivity that has been documented in several ocean basins. This event is associated with changes in the marine carbon cycle, and its initial phase coincides with the Late Miocene Carbon Isotope Shift (LMCIS; Steinhorsdottir et al., 2021). To investigate the Biogenic Bloom in the Tasman Sea, we conducted an integrated study at Integrated Ocean Drilling Program (IODP) Site U1506. We implemented the age model proposed by Sutherland et al. (2019) with an integrated approach (i.e. biostratigraphy, astrocyclostratigraphic tuning) to construct a reliable chronological framework for Site U1506 and to calculate the sedimentation rates across the study interval. Micropaleontological records (benthic foraminifera and calcareous nannofossils) and low-resolution carbon and oxygen stable isotope records on both benthic and planktonic foraminifera (i.e. *Cibicidoides mundulus*, *Trilobatus trilobus* and *Trilobatus sacculifer*) were generated across an interval spanning from the Tortonian (late Miocene) to the Zanclean (early Pliocene). The stable isotope records were compared with the isotope stacks from Drury et al. (2016, 2018) and show a positive correlation. The LMCIS can be recognized as a ~1‰ decrease in the  $\delta^{13}\text{C}$  records between 8.1 and 6.7 Ma. Quantitative and statistical analyses on benthic foraminifera point to increased export productivity and oxygen deficiency at the seafloor associated with the Biogenic Bloom between 7.4 and 5.8 Ma, as inferred from the increase in benthic foraminiferal accumulation rates and the paleoecological analysis.

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## **Trace element availability at the interface between planetary evolution and life emergence**

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*Keywords:* life and planet coevolution, trace elements, cofactors, metabolism, evolution of metabolism, tectonics.

Life and planet have significantly coevolved over time, influencing each other stability trajectory and ultimately maintaining our planet habitable over most of the last 4 billion years. Elemental cycling plays a vital role in this mechanism, with microbes controlling a large portion of the biogeochemical cycles. The majority of the key reactions that control biogeochemistry are carried out by a small set of microbially encoded proteins containing a redox-sensitive transition metal as core catalytic center. Different metal centers (such as Fe, Co, Ni, Zn, Mo, W, V, Cu) are used by biology to access diverse redox couples, utilizing more oxidized compounds as they became available during the planet's evolution. Despite the importance of this process, the relationship between metal availability and metabolic innovation and diversity has not been investigated in detail. Here I will present recent data that suggest a significant coevolution between the geosphere and biosphere analyzed through the lenses of metal use by biology, and suggest possible implication of different mechanisms of metal delivery to the planetary surface through time on the emergence and evolution of metabolism.

## Unveiling the secrets of the Northern Adriatic Sea: the TRETAMARA project for their management, valorization and conservation

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Keywords: Northern Adriatic Sea, Multibeam, Side Scan Sonar, *Pinna nobilis*, Natura 2000.

The Northern Adriatic Sea hosts a rich biodiversity, in both the Italian and Slovenian offshore and nearshore zones. Peculiar habitats, locally known as Trezze and Tegnue, mostly represented by the coralligenous outcrops and colonized by serpulids, red algae, bryozoans, bivalves, and dead corallites of *Cladocora caespitosa*, *Cymodocea nodosa* and *Zostera marina* associated with the presence of *Pinna nobilis* are investigated in the North Italian offshore, and in marine protected areas of Debeli rtič Natural Monument and the Strunjan Nature Park of Strunjan, in Slovenia. This research is carried out in the frame of the INTERREG ITA-SLO TRETAMARA Project, which aims to provide an integrated and strengthened management of the Northern Adriatic marine-coastal habitats with high ecological value. They are characterized by a fragile biological equilibrium, due to the slow-growing calcareous organisms considered as non renewable resources, and the dredging and bottom trawling pressure that strongly threatens the physical characteristics of the habitat and negatively affect the associated biota.

Here we present the preliminary results of cross-border pilot actions supporting biodiversity of these precious marine-coastal habitats. They consist of high quality seafloor images obtained by Multibeam and Side Scan Sonar surveys, aimed at: (1) mapping the Trezze and Tegnue buildups for better understanding their origins, which are still debated (e.g., Gordini et al., 2012; Tosi et al., 2017; Donda et al., 2015 and 2019), and the seagrass meadows and *Pinna nobilis* settlement; 2. Collecting the Management Plans, Conservation Measures, and Regulations actions relating to marine-coastal Natura 2000 areas, aimed at producing a review document for the integrated management of the Northern Adriatic Sea marine habitats with high ecological value. This document will play a key role to promote cross-border sustainability and governance of such fragile environments.

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## History of a foraminiferal invader: the Canal opening, the tsunamis and the global warming

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Keywords: *Amphistegina lobifera*, alien species, core sediments, tsunami deposits, sea surface warming, Suez Canal, Mediterranean Sea.

The opening of the Suez Canal in 1869 led to a massive invasion of the Mediterranean Sea by non-indigenous species (NIS) originating from the Red Sea. Invasive NIS represent a major threat for biodiversity and ecosystem functioning; however, information on invasion history is often lacking, because continuous time-series of population abundance are difficult to obtain and most NIS are detected only after they become extremely abundant, leading to a severe lag time between actual arrival and first finding. Particularly, small-sized invaders are largely overlooked and their early invasion stages, especially when there are failed attempts, remain undetected. This is the case of the benthic foraminiferan *Amphistegina lobifera* Larsen 1976, first recorded from the Maltese Islands (Central Mediterranean) in 2006 (Yokes et al., 2007). Here, we unravel its invasion history using a multi-disciplinary approach to study two sediment cores from Marsamxett Harbour (Malta), radiometrically dated through <sup>210</sup>Pb chronology and analysed with micropaleontological methods. Results show that *A. lobifera* was already present in Malta at the beginning of the 1900s, only a few decades after the opening of the Suez Canal. This makes *A. lobifera* one of the most precocious invaders in the Mediterranean Sea, with significant implications for all previous spreading models, which were based on very imprecise first record data. However, this early colonization attempt probably failed, because *A. lobifera* abruptly disappeared in the sedimentary record. We hypothesize that its disappearance was triggered by an unpredictable geological event, the 1908 Messina earthquake and subsequent tsunamis, of which we could observe some evidences in the cores. The abrupt deposition of about 25 cm of sediment suddenly buried the sea-bottom, adversely impacting the benthic community and possibly affecting the invasion process by *A. lobifera*. After over 30 years, approximately between 1940 and 1945, *A. lobifera* occurred again in the Marsamxett cores; these specimens could have resulted from a local population that survived the tsunami catastrophe, or from an independent introduction event. During the following three decades, the population of *A. lobifera* was still characterised by very low abundances but, since the 1980s, it grew exponentially. Given that the global warming is considered the main forcing factor in the colonization process of the Mediterranean Sea by thermophilic Red Sea invaders, we related *A. lobifera* abundance with trends in sea surface temperature measured in the area during the last fifty years. Results show a strong relationship between Mediterranean Sea warming and *A. lobifera* population density, hence supporting the hypothesis that global warming is playing a dominant role in this bioinvasion process.

Yokes M.B., MERIC E. & AVSAR N. (2007) - On the presence of alien foraminifera *Amphistegina lobifera* Larsen on the coasts of the Maltese Islands. *Aquat. Invasions*, 2(4), 439-441.

## **Role of metazoan and bacteria in cryptic bioconstructions of confined marine settings ("Lu Lampiùne" Cave, Otranto, Apulia)**

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*Keywords:* submarine caves, biostalactite, microfacies, serpulids, bacterial micrite, geobiology, early diagenesis.

The confined conditions of the submarine caves allow the development of cryptic bioconstructions. They have been named "biostalactites" (BSTs) due to their peculiar downward growth from the ceiling or walls of the caves (Guido et al., 2013, 2017; Gischler et al., 2017). BSTs resemble "buildup"-type ecosystems at smaller scale and are receiving increasing attention in the last years since they allow geobiological studies that could clarify the complex relationships between metazoan and bacteria in cryptic bioconstructions of the fossil record. The "lu Lampiùne" cave in Apulia, represents an example of these natural laboratories. Here, BSTs develop through a mutual contribution of metazoan skeletal production and in situ micrite deposition, induced by microbial metabolic activity. These two "building engineers" contribute to form three typical boundstone fabrics: 1) the core, represented by a skeletal-supported boundstone of large *Protula* tubes; 2) an autochthonous micrite (microbialite)/skeletal boundstone, in the downward-facing side; and 3) a pure microbialite boundstone, in the upward-facing side of the biostalactite.

The boundstone in the core consists of a braided frame formed by *Protula* tubes cemented each other to form a strong structure that offers an ideal substrate for the colonization of further organisms. In turn, the decomposition of the organic matter, produced by this complex association, stimulates the development of heterotrophic bacteria that induce autochthonous micrite deposition. In addition to these induced carbonate biomineralization processes, the Fe/Mn autotrophic and chemoheterotrophic bacterial activity mediate the mineralization of Fe/Mn crusts and *Frutexites*-like structures.

Carbonate vs Fe/Mn oxides deposition records variable chemical composition of the cave seawater. Phases of carbonate saturation coincide with the skeletal/microbialite growth and early cement deposition. These alternate with phases of dissolution and precipitation of Fe/Mn structures that indicate presence of acidic waters.

The uniformity of the organisms, microstructures and biochemical signals, from the base to the growing tip of the biostalactite, suggests a uniform style from its inception (c. 6,000 years ago) to the present-day.

Gischler E., Heindel K., Birgel D., Brunner B., Reitner J. & Peckmann J. (2017) - Cryptic biostalactites in a submerged karst cave of the Belize Barrier Reef revisited: pendant bioconstructions cemented by microbial micrite. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 278, 34-51.

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## Evolution of the forested landslide slope along the Parma Torrent: first results of an integrated approach

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**Keywords:** Forested slopes, landslides, Northern Apennine, GIS.

Landslides are one of the main geological features characterizing the Northern Apennines, for what concerns the hydrogeological instabilities. In order to study the evolution of a forested landslide slope along the Parma Torrent, Northern Apennines western sector we set up an integrated approach using dendrogeomorphological and GIS analyses. Active and re-activating landslides in the Northern Apennines are mainly characterized by events starting as rotational or translational sliding and ending with earth flows, mainly depending on the lithology (flysch rocks and clayey formations are widespread in the median belt of the chain) and on the structural characteristics. Landslide often interact with human settlements, towns, and agriculture, resulting more in infrastructural damages and property loss than fatalities. Gravitational processes directly interact also with the main feature characterizing the landscape of the internal areas of the Apennines, i.e. forests. Forest cover in the Northern Apennines western sector is mainly characterized by beech (*Fagus sylvatica*) in the upper altitudinal portion from approximately 1000 m a.s.l. up to the treeline (approximately 1600 m). In this altitudinal belt the forest cover reaches up to 90% of the available land surface, whereas above the treeline, the land surface is characterized only with herbaceous covers and more exposed to the meteorological agents directly influencing the geomorphological surface processes. Between 200 and 1000 m a.s.l. the forest cover is dominated by oak (*Quercus* spp.), hornbeam (*Carpinus betulus*) and chestnut tree (*Castanea sativa*). In this belt, forest cover is limited by agriculture and urban settlements especially between 200 and 600 m, where forests are generally limited to steep slopes and occupy less than 50% of the available surface (Northern Apennines, western sector). At the study site located in this latter belt, we could reconstruct the spatial and temporal dynamics of a landslide event occurred along the Parma Torrent incision inducing gravitational processes at the toe of the Carobbio landslide, by means of dendrogeomorphology and GIS analysis. This study evidences the strict interaction between landslide processes and forests, with the possibility of obtaining important information on landslide evolution through time and its spatial dynamics.



## Sensitivity of benthic foraminifers in environmental biomonitoring of coastal areas in the northern Adriatic Sea (Italy)

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**Keywords:** benthic foraminifers, environmental biomonitoring, coastal areas, TOC, Heavy metal.

Coastal marine environments, including lagoons, are fragile ecotones where the increase in human activities has led to pollution as they serve as “reservoirs” for the majority of coastal terrestrial runoff. Studying the health of these environments relies increasingly on bioindicators able to signal changes caused by human activities. Among these, benthic foraminifers play a role that is improving due to numerous studies conducted in the Mediterranean and surrounding areas. Recently, some authors proposed to assign benthic foraminifers to diverse Ecological Groups (EG), mainly related to the total organic carbon (TOC) content (Jorissen et al., 2018; Bouchet et al. 2021).

A seasonal survey during 2013 was performed to analyse benthic living foraminifera in the Gulf of Trieste (north Adriatic Sea) by comparing two marine coastal sites: the Marine Protected Area of Miramare and a site close to a sewage outfall (Melis et al., 2019). Although foraminifera varied following a “natural” cycle over the seasons, the major differences between the two stations were related to potentially toxic elements and TOC concentrations. *Ammonia tepida*, *Bolivina* spp., *Bulimina* spp. and *Eggerelloides scaber* were the most opportunistic species.

In addition, further research was conducted in a fish farm of the Marano and Grado Lagoon where Hg bioaccumulation was detected in fish species of commercial interest. Low abundances of foraminifers were observed in relation to higher Hg and TOC concentrations. *Ammobaculites exiguus*, *Ammoscalaria runiana* and *Elphidium granosum* tolerate higher bioavailable Hg concentration. *Haynesina germanica* seems to better tolerate hypoxic/anoxic conditions at the bottom sediments occurring in the most isolated part of the fish farm.

Bouchet V.M.P., Frontalini F., Francescangeli F., Sauriau P.-G., Geslin E., Alves Martins M.V., Almogi-Labin A., Avnaim-Katav S., Di Bella L., Cearreta A., Coccioni R., Costelloe A., Dimiza M.D., Ferraro L., Haynert K., Martínez-Colón M., Melis R., Schweizer M., Triantaphyllou M.V., Tsujimoto A., Wilson B. & Armynot du Châtelet E. (2021) - Indicative value of benthic foraminifera for biomonitoring: Assignment to ecological groups of sensitivity to total organic carbon of species from European intertidal areas and transitional waters. *Mar. Poll. Bull.*, 164, 112071.

Jorissen F.J., Nardelli M.P., Almogi-Labin A., Barras C., Bergamin L., Bicchi E., El Kateb A., Ferraro L., McGann M., Morigi C., Romano E., Sabbatini A., Schweizer M. & Spezzaferri S. (2018) - Developing Foraminifera-AMBI for biomonitoring in the Mediterranean: species assignments to ecological categories. *Mar. Micropal.*, 140, 33-45.

Melis R., Celio M., Bouchet V.M.P., Varagona G., Bazzaro M., Crosera M. & Pugliese N. (2019) - Seasonal response of benthic foraminifera to anthropogenic pressure in two stations of the Gulf of Trieste (northern Adriatic Sea): the marine protected area of Miramare versus the Servola water sewage outfall. *Mediterr. Mar. Sci.*, 20, 120-141.



## The dark layer at the Messinian Zanclean boundary: a glimpse on the refilling of the Mediterranean at the end of the Messinian salinity crisis

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**Keywords:** Miocene-Pliocene boundary, dark layer, termination of Messinian.

The Messinian salinity crisis (MSC) was a geological event characterized by the deposition of huge volumes of evaporites in the Mediterranean basin. After decades of scientific debate, the consensus model (CIESM, 2008) proposed a new stratigraphic framework, and the MSC was subdivided in three stages (Manzi et al., 2013; Roveri et al., 2014). Stage 3 started at around 5.53 Ma, and its uppermost part corresponds to the “Lago-Mare” phase, characterized by the occurrence of brackish shallow water ostracods of Parathetyan origin. These deposits are sharply overlain by Zanclean open marine fine-grained sediments recording the establishment of open marine condition at the end of the MSC at 5.33 Ma. The interpretation of such abrupt transition is debated: it could be a catastrophic reflooding of the Mediterranean according to some authors or a gradual refilling of the basin according to others. In many Mediterranean sections, the Messinian-Zanclean boundary is marked by a poorly investigated dark layer (DL), that can provide insights on the mechanism responsible for the refilling of the Mediterranean at the end of the MSC. We investigated DL in six sections along a W to E transect of the Apenninic foredeep trough an integrated micropaleontological, petrographic and ichnological approach.

Preliminary results show that, although the texture, structure, and lithological composition of the DL change from section to section, this is always interbedded between the uppermost Lago Mare and the basal Zanclean sediments through a sharp and conformable boundary, arguing against a catastrophic refilling of the Mediterranean. Moreover, the DL is strongly bioturbated, with crypto and large burrows filled with Pliocene basal mud (*Reticulofenesta zancleana*), which suggests starved condition at early Zanclean. Finally, the preliminary results on the association of benthic foraminifera and on the P/B ratio, indicate a gradual increase in bottom oxygen content and in depth from the top of the DL to the lowermost Pliocene.

CIESM 2008. The Messinian Salinity Crisis from mega-deposits to microbiology - A consensus report. N° 33 in CIESM Workshop Monographs [F. Briand, Ed.], 168 p., CIESM Publisher, Monaco.

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## **Benthic microbial community structure across the Adriatic sea and the role of terrigenous inputs**

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*Keywords:* Coastal environment, sediments, prokaryotic community structure, nutrients.

Flowing rivers represent the first vector of transport of sediments into the marine environment. With them, huge quantities of substances like nutrients, organic matter (DOC and POM), and chemical compounds are transferred. All these spread along the marine coastal system, where they can interact with benthic communities under different depositional processes, causing ecological shifts in their structure. To assess the influence of different depositional environments, trophic resources, and possible contamination by human activities on the large-scale distribution of prokaryotes, we investigated the variability of benthic prokaryotic communities (Bacteria and Archaea) in the surface sediments of the Middle and Southern Adriatic Sea, along the Italian coast. Results obtained through biochemical investigations show an environment rich in nutrients, with the trophic status much similar to that found in eutrophic environments. This was also confirmed from the prokaryotic diversity found, suggesting a strong role of the prokaryotic community in organic matter cycling. The large-scale microbial diversity dataset was correlated to different metadata and geochemical data to understand which factors affected the prokaryotic abundance and distribution and the organic matter load. Linear relationships between variables were present only for a limited range of values. Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> concentrations in the sediments, grain size distribution, and distance from the coastline were identified as the major factors explaining the variation in the prokaryotic distribution in the surface sediment. These variables were associated in Adriatic sediments with the Alpine and Apennines river inputs and strongly correlated with deposits from the Po river, which suggest a strong influence in controlling the characteristics of the sediments distribution, trophic resources, and prokaryotic abundances. These observations implicate a strong influence on the function performed at the interface between water and sediments and the flux of nutrients to the entire benthic community.

## **A geomorphological study of graben structures offshore the Maltese Archipelago with characterisation of associated physical habitats**

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*Keywords:* graben structures, habitat mapping, tectonic geomorphology, submarine geomorphology, cold water corals, seabed fluid flows.

The submarine realm represents more than 70% of the Earth, but its majority has yet to be mapped and studied. The Seabed 2030 initiative is the key long-term international project with a mandate to map the entire ocean floor. If we focus on the Mediterranean Sea, several areas have not been investigated yet. Among them, the areas around the Maltese Archipelago, in the central Mediterranean, have been poorly investigated, representing quite an important geographical and geomorphological gap in knowledge. The Life BaHAR for N2K project, commenced in 2013 and concluded in 2018, was oriented on extending already existing marine Sites of Community Importance (SCIs), if necessary, and designating new marine areas as SCIs within Malta's waters to form part of the Natura 2000 network. Thanks to the data collected within this project, I was able to perform a geomorphological study over a portion of the Malta Graben System. The study area covers part of the north-west seafloor offshore Gozo, and a larger portion of the south-west bottom offshore the Maltese Islands. In particular, three specific areas have been investigated: Area 1, along the northern margin of the Malta Graben; Area 2, covering part of the southern margin of the Malta Graben; and Area 3, which is NW of Gozo in the proximity of the North Gozo Graben. The main goal of this project has been the identification of the main morphological features, and associated driving processes, present in the area to provide a geomorphological characterisation of this part of the Malta Graben System. In addition, I focused on the identification of those areas which deserve a special attention as hypothetically associated to sensitive habitats.

## Calcareous nanofossils and geochemistry as paleoclimatic tracers across the Eocene-Oligocene transition (IODP Site U1509, Tasman Sea)

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**Keywords:** calcareous nanofossils, Eocene-Oligocene, biochronology, paleoclimate, Tasman Sea

The Eocene-Oligocene transition (EOT; lasted ~790 kyr) is one of the most prominent climate transitions of the Cenozoic, occurred ~34 Ma. This event documents a rapid drop in temperature and the establishment of the first semi-permanent ice-sheet on the Antarctic continent (Westerhold et al., 2020). During this time, the altered conditions on the biogeochemical cycles and ecosystems deeply affected the marine and terrestrial biota. Among the marine dwellers, calcareous nanoplankton exhibit significant fluctuations in the assemblage resulting from a long-term cooling and modifications in the sea-surface water structure, suggesting a cause-effect relationship between the onset of the first sustained Antarctic glaciation and the phytoplanktonic response. In this work, we present the results of a detailed biochronological, paleoclimatic and morphometric analyses on calcareous nanofossils from IODP Site U1509 (Tasman Sea; Sutherland et al., 2018).

Our bio-magnetostratigraphic results, consistent with shipboard data, were compared along with other records to obtain a clearer biochronological global perspective. We also generated a high-resolution calcareous nanofossil and geochemical datasets ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$  and %  $\text{CaCO}_3$ ) with the final aim to provide a paleoclimatic overview of the study area, spanning from the late Eocene to the early Oligocene. According to major trends and shifts in the assemblage, the ~5 Myr study interval was subdivided in 4 distinct phases, which were also identified based on changes detected in: 1) a number of diversity indices, 2) the warm-oligotrophic taxa abundance, 3) the principal component (PC1 and PC2) scores, 4) bulk stable isotopes and carbonate content. The observed changes were interpreted as an overall decline of warm-oligotrophic communities and, conversely, the incoming of genera better adapted to cooler and more eutrophic conditions. The most prominent shift in the assemblage occurred during a time window of ~520 kyr, the *precursor phase*, with relatively high bulk  $\delta^{18}\text{O}$  and % $\text{CaCO}_3$  values.

Among the investigated taxa, *Clausicoccus subdistichus* gr. has proven to be one of the most useful biostratigraphic and paleoenvironmental proxy during this crucial time. Comparative morphometry was performed on this group from 108 samples recovered from different sites located in the Atlantic, Pacific and Indian oceans. This latter analysis provided key information on *Clausicoccus* sensitivity to changes in the sea-water carbon geochemistry and surface marine trophic conditions.

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## Are foraminiferal tests selected or randomly picked by *Sabellaria alveolata* (Linnaeus) to form its arenaceous bioconstructions?

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**Keywords:** arenaceous bioconstruction, *Sabellaria alveolata*, foraminiferal tests, alien species, Mediterranean Sea.

The honeycomb worm *Sabellaria alveolata* (Linnaeus, 1767) is a littoral reef builder widely spread in the Atlantic and Mediterranean coasts, where it plays a key functional role for coastal protection and habitat provision. In the Italian peninsula, this polychaete occurs along both the Tyrrhenian and Adriatic coasts and in southern Sicily, where it builds wave-resistant reefs made of sand-sized grains (Ingrosso et al. 2018). The grains, which include foraminiferal tests and biogenic remains, are kept suspended by the wave motion in the water column, from where they are picked by the polychaete and organically cemented to form the agglutinated tubes.

For this work, 12 small samples of bioconstruction were collected in two sites of southern Sicily, along with 12 samples from the nearby sea-floor. The arenaceous tubes were taken from two distinct portions of the bioconstruction: bottom and top; similarly, sediment samples were collected at two distance levels from the bioconstruction: closer (< 5m) and farther (> 5m). The main purpose was to verify if *S. alveolata* actively selects foraminiferal tests to build its arenaceous tubes, and if the tests are chosen based on their morphology. To this purpose, foraminiferal tests contained in both types of collected samples were identified, quantified, classified into functional morphogroups and statistically treated.

Results document a higher concentration of foraminiferal tests agglutinated within *S. alveolata* tubes than in sediment, with a clear preference for biconvex and sphaerical morphogroups. The foraminiferal genera *Ammonia*, *Cibicides*, *Cibicoides*, *Globigerina* e *Globigerinoides* resulted the most abundant in the bioconstruction. We hypothesize that the high proportion of biconvex and spherical tests in the bioconstruction was probably related to the different hydrodynamics of the grains kept in suspension by the wave motion, which made them more available for the capture by the polychaete in a continuous recycling mechanism (Reuter et al., 2010). Furthermore, among the different foraminiferal tests agglutinated in the arenaceous tubes, we observed sporadic specimens of *Amphistegina lobifera* Larsen, a non-indigenous foraminifer native to the Red Sea, that has been recently recorded in southern Sicily (Guastella et al. 2019). This unexpected finding demonstrates how quickly alien species become part of the new invaded environment.

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## Calcareous nannofossils at IODP Site U1553, a reference paleoceanographic record for the Paleogene

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*Keywords:* calcareous nannofossils, Southern Ocean, Paleogene.

In January 2020, International Ocean Discovery Program (IODP) Expedition 378 drilled in South Pacific and recovered a continuously cored, multiple-hole Paleogene sedimentary section at Site U1553 (Thomas, Röhl, Childress, et al., 2020). The aim was to replicate the sedimentary record of DSDP Site 277, the best known Paleogene paleoceanographic site in the South Pacific, drilled during Leg 29 (Kennett et al., 1975). From this site, classic oxygen isotope records were generated that first defined the climatic evolution through the Eocene (e.g., Shackleton & Kennett, 1975). Improved coring technologies and core-log integration resulted in the development of multiple core stratigraphic splices representing a more complete succession than the single succession of Site 277. This area in the South Pacific Ocean is critical for high-latitude climate reconstructions across the Paleocene to late Oligocene. Research on Site U1553 is in-progress for studying in detail the major events preserved in this high-latitude sedimentary record (Hollis et al., 2015). Here we report on the preliminary results of a study on calcareous nannofossil assemblages in an expanded upper Eocene to upper Oligocene sequence. The biostratigraphic data confirm the validity of the biozonation scheme proposed for the Southern Ocean (Fioroni et al., 2012) and suggest that further refinements on biostratigraphy can be obtained, thanks to the rich and well preserved nannofossil assemblages observed. In a preliminary paleoecological analysis, performed at low resolution, the considered major groups, each including cool, temperate, eutrophic and oligotrophic taxa, provide a revealing signal for paleotemperature and nutrient concentration in line with previous studies at high latitude sites (Villa et al., 2014). Further analyses at high resolution will certainly help in reconstructing changes in South Pacific temperature, circulation, and productivity associated with the greenhouse–icehouse transition (Eocene/Oligocene) and the early Oligocene.

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**S19.**  
**Paleo-climatic transitions**

*CONVENERS AND CHAIRPERSONS*

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## Evidence of the Carnian Pluvial Episode from the sedimentary record of the Southern Alps and Outer Dinarides

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Keywords: paleoclimate, stratigraphy, Late Triassic, Tethys, carbonate and siliciclastic systems.

The Carnian Pluvial Episode (CPE) represents one of the recently more attracting topics for researchers studying the Earth system evolution and climate changes. It consists of a perturbation of the Triassic arid to semi-arid climate toward more wet conditions lasted slightly more than one million of years. The global impact of this episode has been documented by now, indeed the geological record holds different related proxies. At least three negative excursions of the  $\delta^{13}\text{C}$  isotope curve have been detected, connected to perturbations of the global carbon cycle. These affected the mega-monsoonal circulation in the Tethys realm, increasing the rate of precipitation and the siliciclastic runoff to the basins. Changes in carbonate factories of shelf carbonates triggered a crisis of high-relief carbonate platforms, most of them being replaced by ramp depositional systems. Biological turnover also occurred, with extinctions and radiations.

Traces of the CPE are decipherable in the Southern Alps, framed in a high-resolution sequence stratigraphic and biostratigraphic framework, and correlations with the Outer Dinarides succession can be established.

In the basins, the CPE is announced by local anoxia and by a first pulse of immature siliciclastics, slightly preceded by a negative carbon isotope excursion (NCIE) in the latest *T. aonoides* zone. A 3<sup>rd</sup> order sea-level fall anteceded the onset of the CPE, exposing platform-top areas to subaerial erosion, with common development of karst surface and spodic paleosols, and allowing the deposition of forced regression units terrigenous to mixed carbonate-ramp deposits. During the following lowstand conditions, skeletal grainstones and hybrid sandstones dominated shallow areas, while bauxite horizons developed in still emerged areas. Deeper areas were infilled by mud-dominated low-density turbidites, and local basins were progressively filled. During the following transgression, a shift from inner to outer carbonate ramp is recorded on a wide area. Plant debris, ambers and coal horizons are common in this interval. A new pulse of siliciclastics, likely associated to a second NCIE and increased runoff, characterizes the succession upward (late *A. austriacum* Zone). A third NCIE has been recorded at the Julian/Tuvalian boundary, about at the end of the transgression. During the subsequent highstand, a general regressive shallowing upward trend is observed, often accompanied by the re-establishment of shallow carbonate ramps and leading to a regional flattening of the paleotopography. The upward succession is marked by a new sea level fall, moving the shoreline basinward for tens of kilometers and producing a sharp unconformity. Alluvial to marginal marine environments were established widely. The regressive interval is likely associated with a fourth NCIE (*T. subbullatus* Zone). Above, evaporites and peritidal carbonates occurring in most of the Tethyan region reflect an arid to semi-arid climate.

## The last deglaciation in Italy: timing and pattern from a precisely dated stalagmite

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**Keywords:** palaeoclimate, speleothems, glacial termination, Holocene, Bølling-Allerød, Younger Dryas.

The last deglaciation (Termination I, T-I) was the most recent global-scale climate transition. It involved a drastic temperature increase guiding massive melting of ice sheets, with a concurrent reorganization of inter- and intrahemispherical atmospheric and ocean circulation patterns.

T-I lasted ~3.0 ka (ka = kiloyears before present) in Greenland (NGRIP, 2007), although it was not a linear process. A rapid temperature increase at 14.6±0.3 ka (Bølling-Allerød, BA) was followed by a return towards glacial-like conditions (12.2±0.3 ka, Younger Dryas, YD), before the last warming that led to the Holocene (11.7±0.1 ka). Other secondary climate oscillations characterized T-I too (Cheng et al., 2020). Some of these intra-deglaciation global warmings were particularly rapid, at times occurring at centennial or even decadal timescale. This provides an interesting comparison with the current climate change.

Yet, it is not clear how T-I-related dynamics occurring at the polar regions and/or in the oceans impacted terrestrial environment at mid latitudes, in terms of rainfall and temperature variation and related environmental and ecological changes. This is especially true for the Mediterranean area, considering that its climate is connected – and controlled – by processes occurring in the Atlantic and Arctic. In Italy, T-I records of adequate chronological resolution are virtually absent.

We here present a novel speleothem record from Sant'Angelo Cave (SA1, Ostuni, Apulia) spanning from 47.7±0.1 to 8.9±0.9 ka. In the period from ~20 to ~10 ka, multiple U-Th datings (n=22) resulted in a final age model with an average uncertainty of <0.3 ka and a resolution of ~25 years. Climate proxies ( $\delta^{18}\text{O}$ , n=1045) were anchored to this chronology. The reliability of SA1- $\delta^{18}\text{O}$  in recording palaeoclimate information was ascertained by a statistically grounded inter-cave replication test with a recently published speleothem record from a nearby site (Columbu et al., 2020). The interpretation of SA1 allows to: 1) accurately and precisely constrain, for the first time in Italy, the timing of the T-I climate pattern; 2) evaluate the impact of BA, YD and Holocene inception in southern Italy, as well as other associated events, especially in terms of rainfall variability; and 3) understand the spatio-temporal relation between the Atlantic/Greenland domain, the Mediterranean realm and monsoonal areas throughout the deglaciation. We discuss this new record within the framework of previous regional studies based on glacial (NGRIP, 2007), marine (Martrat et al., 2007) and continental proxies (Allen et al., 1999; Cheng et al., 2016), with the aim of providing a better comprehension of the timing and structure of T-I in Italy and, by extension, of the central and western Mediterranean area.

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## **IODP Exp. 374 provides clues into the dynamics of the Antarctic Ice Sheet during Cenozoic climate transitions**

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*Keywords:* International Ocean Discovery Program, Eurofleets, Ross Sea, Antarctica.

The Eurofleets ANTSSS (Antarctic ice Sheet Stability from continental Slope process investigation) 2017 cruise and the IODP (International Ocean Discovery Program) 2018 Expedition 374 recovered new geological, geophysical, and oceanographic data from a latitudinal and depth transect across the continental shelf, slope and rise of the Ross Sea, Antarctica.

This transect is located along one of the largest glacial valleys cut into the continental shelf by West Antarctic Ice Streams that feed into the Hillary Canyon, which debouches downslope onto the continental rise. It is also located along the oceanward flow pathway of dense and cold water, forming in the Ross Sea polynya and mixing with Circumpolar Deep Water at the continental shelf edge. The new morphobathymetric geological and oceanographic data highlight that processes acting here during glacial and interglacial cycles likely drove large-scale shifts in outer shelf and canyon head processes, and the build-up of channel-levees on the continental rise.

The IODP Exp. 374 sites U1521 and U1522 recovered a Miocene to Plio-Pleistocene geological record of past expansion and retreat of ice streams emanating from the East and West Antarctic Ice Sheets across the Ross Sea continental shelf. Site U1523 targeted a Miocene to Pleistocene sediment drift on the outermost continental shelf and informs about the changing vigor of the eastward flowing Antarctic Slope Current (ASC) through time, a key control on regulating heat flux onto the continental shelf. Sites U1524 and U1525 cored a continental rise levee system near the flank of the Hillary Canyon, with a near-continuous record of the downslope flow of Ross Sea Bottom Water and turbidity currents, but also of ASC vigor and iceberg discharge.

A 20 cm-thick tephra matches a c. 1.3 Ma deposit on the caldera rim of the Chang Peak volcano 1300 km from the U1524 coring site adds a new marker for dating, correlation, and synchronization of marine and continental early Pleistocene records of West Antarctica.

Exp. 374 sediments are providing key chronological constraints on the major Ross Sea seismic unconformities, enabling reconstruction of paleo-bathymetry and assessment of the geomorphological changes associated with Neogene ice sheet and ocean circulation changes. Exp. 374 results are fundamental for improving the boundary conditions of numerical ice sheet, ocean, and coupled climate models, which are critically required for understanding past ice sheet and global sea level response during warm climate intervals. Such data, and improved model skill, will enable more accurate predictions of ice sheet behavior and sea level rise anticipated with future warming.

## Sedimentary processes at the Isfjorden continental margin: preliminary results from lithological study of two long Calypso cores

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**Keywords:** Svalbard western margin, Isfjorden Drift, sedimentary processes.

The main objective of this study is to reconstruct the Late Quaternary (<60 ka) palaeoceanographic and paleoclimatic variability recorded in the Isfjorden sediment drift located on the western margin of Svalbard (Arctic). The study is based on the sedimentological analyses on two calypso cores: core GS191-02PC, located at 1320 m water depth, that was collected during the expedition of the R/V G.O.Sars, in the framework of Eurofleets-2 PREPARED Project (Lucchi et al., 2014), and core CAGE-19-3-KH-15-GPC01, located at 1580 m water depth, that was collected during the “Calypso giant piston coring in the Arctic-Atlantic gateway” expedition on the R/V Kronprins Haakon (Knies & Vadakkepuliambatta, 2019).

The cores were studied with X-ray, physical properties obtained through a Multi-sensor core logger (magnetic susceptibility and wet bulk density), digital photographs of the fresh sediment surface, visual logging, and sediment composition through XRF-core scan (chemical composition) and XRD analyses (clay mineral assemblage). A high-resolution age model was reconstructed for core GS191-02PC (Caricchi et al., 2019). In this poster, we present the results of sedimentological analysis from the two calypso cores providing information on the down-slope (glacial) vs along-slope (contour currents) sedimentary processes that occurred at the Isfjorden drift during last 60 ka.

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## Alluvial megafans in Europe at the transition between LGM and Late Glacial

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**Keywords:** Alps, Venetian-Friulian Plain, Po Plain, Carpathian Basin, Hungarian Plain, Last Glacial Maximum, incised valleys.

The end of the Last Glacial Maximum (LGM) brought a significant change in the dynamics of most of the alluvial systems of the northern hemisphere, even in the ones not directly connected to glaciers or without a glaciated mountain catchment. We analysed how the alluvial megafans of Europe responded for their sedimentary and geomorphological characteristics to the passage from LGM to Late Glacial conditions. Quaternary megafans are documented at the foot of the southern Alps (i.e. Po Plain and Venetian–Friulian Plain) and along the Carpathian Mountains (i.e. Little and Great Hungarian plains, Getic and Walachia plains).

In Northern Italy a robust radiocarbon chronology is available for Tagliamento, Piave and Brenta megafans, demonstrating that they experienced a strong depositional phase between 29 and 17.5 ka BP, when the Alpine glaciers stationed at the mouth of their valleys and the rivers played as glacial outwashes. Significant variations occurred in the alluvial systems of northern Italy already when the glaciers had just started to withdraw from their most external moraines, soon after 21 ka cal BP (Fontana et al., 2014). All the megafans along the southern side of the Alps experienced a dramatic sedimentary starvation since the beginning of Late Glacial (21-14.5 ka cal BP), when the rivers entrenched along deep incised valleys up to the distal sector of the plain. Thus, the megafans of northern Italy represent relict products of the LGM, that were mainly built by the sediment eroded by the glaciers in the Alps.

In the Carpathian Basin the megafans have been affected also by significant tectonic subsidence of the distal plain and, if compared to the ones of the southern Alps, the fluvial systems are related to larger mountain catchments. These were not severely glaciated during the LGM and an important depositional phase occurred in several alluvial systems also along the whole Late Glacial (19-11.7 ka cal BP), probably sustained by periglacial and aeolian processes. This is the case of the Maros megafan (Kiss et al., 2014), which formed in the Great Hungarian Plain, between Romania and Hungary, and is the largest megafan of Europe (7000 km<sup>2</sup>). A similar evolution occurred also in the megafan of Raba River, which was built in the Little Hungarian Plain, and contrasts with the Danube River, that formed its megafan in the same region but it has been strongly active also during the Holocene.

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## **LGM - Holocene sedimentary dynamics by multidisciplinary analysis of three box cores collected East to the Hillary Canyon (Eastern Ross Sea, Antarctica)**

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*Keywords:* Antarctica, Ross Sea, Ross slope, box cores, sedimentology.

The presence of different types of glacial and sub-glacial features near the shelf edge indicates that the Western Antarctic Ice Sheet (WAIS) was grounded near the shelf break in many sectors of the Eastern Ross Sea (ERS) during the Last Glacial Maximum (LGM) (Shipp et al., 1999; Mosola & Anderson, 2006; Halberstadt et al., 2016; Anderson et al., 2018; Gales et al., 2021). However, mechanisms and timing of the post-LGM retreat are still debated. Studying sediments collected along the continental slope could help to reconstruct the LGM and post-LGM history of the ice sheet.

This study focused on the analysis of three box cores collected east of the Hillary Canyon, which carves the ERS continental slope and is connected to the Glomar Challenger and Pennell Troughs on the shelf, south-east to the Iselin Bank. Multidisciplinary analysis (grain size, organic matter, biogenic silica and water content, magnetic susceptibility and chemical composition (XRF core scanner)) were conducted in order to reconstruct the sedimentary dynamics. Three samples for each box core were dated by using organic matter (<sup>14</sup>C AIO dates). Here, we present the results of these analysis.

These box cores were collected during the XXIX PNRA (National Antarctic Research Program) expedition (2013-2014) and studied in the frame of the ROSSLOPE II (2013/AN2.01) PNRA project and the STREAM Project (Late Quaternary evolution of the ocean-ice sheet interactions: the record from the Ross Sea continental margin, Antarctica; period 2019-2021). The latter is funded by the Italian Ministry of Foreign Affairs and International Cooperation and the National Research Foundation of Korea.

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## **Isotope Stratigraphy (C and Sr isotopes), Facies analysis and Rudists distribution in the Upper Cretaceous shallow water carbonates of the Friuli Carbonate Platform**

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*Keywords:* Upper Cretaceous, Rudist bivalves, Isotope stratigraphy.

Fossil carbonate platforms preserve a detailed record of paleoenvironmental, paleoclimatic and biotic changes. However, disentangling the complex information contained in these sedimentary rocks require a robust stratigraphic framework. Isotope stratigraphy is being increasingly used as a stratigraphic method, additional to biostratigraphy, to help precisely constrain the dating and improve correlations of shallow water carbonate successions. During the Late Cretaceous, rudist bivalves dominated shallow water carbonate environments, however, they showed a fluctuating record of peaks in abundance and phases of demise, a cause of which is still not completely understood. Furthermore, the low-Mg calcite shells of these bivalves are valuable palaeoarchives that have the potential to help reconstructing environmental and climatic changes throughout the Cretaceous.

In this work, we present the results of a study on a well exposed carbonate succession cropping out in the Karst region, in the vicinity of the city of Gorizia and belonging to the fossil Friuli Carbonate Platform. In order to build a high resolution Sr and C isotope records, we have sampled the sections with high resolution (< 50cm), which allowed us to define the stratigraphy of these deposits with unprecedented precision. Furthermore, we carried out facies, geochemical analyses and investigated rudists distribution in the examined succession.

The data obtained allowed us to:

- Precisely date the identified bioevents.
- Correlate the bioevents and facies evolution with those identified in coeval carbonate platforms across the perimediterranean area.
- Establish a stratigraphic framework of the distribution of rudist-rich intervals.
- Build a Late Cretaceous paleotemperature record for the Friuli carbonate Platform.



## Extensive episodic melting of the paleo Svalbard-Barents Sea Ice Sheet during last 60 ky

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Keywords: Arctic, MIS-3, MWP-1a, MWP-19ka, Heinrich events, paleoclimate.

The recent depositional architecture of the north-western Barents Sea continental margin derives from late Quaternary climate changes producing alternating deposition of glacial diamicton and debris flows associated with shelf-edge glaciations, and bioturbated, biogenic-rich sediments deposited during interglacial conditions. Yet, several m-thick, laminated sediments recovered along the whole margin, were associated with intense release of turbid meltwaters (plumites deposition) associated with ice sheet decay occurring during glacial terminations and/or transitional phases such as the Marine Isotope Stage (MIS)-3. A high-resolution age model allowed the identification and correlation along the margin of prominent meltwater events including the MWP-1a (Lucchi et al., 2013, 2015), the MWP-19ka (Caricchi et al., 2019), and Heinrich-like events coeval with H2, H4, H6, but associated in this area with episodes of ice sheet instability and melting. Sedimentological and compositional analyses revealed new insight on the paleoclimate variability during MIS-3, its feedback on the paleo Svalbard-Barents Sea Ice Sheet, and the impact of extensive meltwater events on the paleoenvironment, and hydrographic characteristics.

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## Rock-magnetism as indicator of the Norian-Rhaetian paleoclimate

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Keywords: Upper Triassic, paleomagnetism, marine geochemistry.

Rock magnetic investigations of lacustrine and marine sediments are known to provide paleoclimatic information (e.g., Vigliotti et al., 1999, Abrajevitch et al., 2013; Chang et al., 2018). In order to obtain information about the climate perturbation around the Norian/Rhaetian boundary (Upper Triassic) we investigated the magnetic properties of the pelagic carbonate sequence of the Pignola-Abriola section (Lagonegro basin, southern Italy). The late Norian-early Rhaetian is indeed characterized by a biotic turnover involving both marine and terrestrial fauna, such as ammonoids, conodonts, bivalves and vertebrates. The Norian-Rhaetian crisis occurred in concomitance of a general  $\delta^{13}\text{C}_{\text{org}}$  perturbation that led to a negative carbon isotope excursion at the NRB, associated with the disappearance of bivalve *Monotis* and the first appearance of conodont *Misikella posthernsteini*. The cherty-limestone sequence of Pignola-Abriola section, candidate GSSP for the Rhaetian Stage (Rigo et al., 2016), has been broadly studied for both biostratigraphy, geochemistry and magnetostratigraphy (e.g., Maron et al., 2015; Rigo et al., 2016; Zaffani et al., 2017). The rock-magnetic data here presented (ARM, IRM, X, etc.) provided new paleoclimatic information (about weathering, runoff, microbial activity, etc.), that have been compared to the latest geochemical data (CIE, Ce/Ce\*, V/Cr, Mo/U, etc.) from Pignola-Abriola.

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## The Ross Sea sector oceanography: glacial vs present day

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*Keywords:* paleoceanography, ocean modelling, paleoclimate.

During the Last Glacial Maximum (LGM, 21'000 yrs BP) the Antarctic ice sheet was extended over the continental shelves. In the Ross Sea sector, only a restricted portion of the continental shelf was ice free, restricting main coastal circulation to the continental slope. How this impacted on the oceanic circulation in the open ocean and on the basal melting at the grounding line of the Antarctic ice sheet remains unknown.

Here we present the implementation of the ocean model MITgcm on a regional grid of the Ross Sea at 5 km resolution. The numerical model includes the sub ice-shelf cavity and interactive sea-ice, while tides are not accounted for. This implementation was used to run a transient control simulation over 1993-2018 forced by state-of-the-art atmospheric and ocean reanalyses. As for the LGM, the model was spun up with steady-state climatic conditions and run transiently for 20 years. Atmospheric and oceanic forcing were taken from a global climate transient simulation (TraCE-21ka, Liu et al., 2009).

The comparison of model output with oceanographic in situ data, demonstrates that it is able to simulate the main features of the oceanic circulation: the warm Circumpolar Deep Water (CDW) is advected by the southern branch of the Ross Sea Gyre towards the shelf-break, where it crosses the Antarctic Slope Front (ASF) and intrudes onto the shelf where it mixes with ambient waters (mCDW). In the Western shelf, production of High Salinity Shelf Water (HSSW) occurs by wind-induced brine rejection in winter months. The HSSW and mCDW are advected below the Ross ice shelf at different depths, the first at the grounding line, the second at the front, therefore impacting in different ways on ice shelf dynamics.

A preliminary comparison of the present-day and LGM runs shows that the simulated LGM circulation was totally different. Almost all the shelf was covered by grounded ice, except for the three main troughs in the Western side: Drygalski, Joides, Pennel (Halberstadt et al., 2016), where sub-ice shelf cavities presumably were developed. The CDW in the open ocean was ~2 °C cooler than the present, and ~2 PSU saltier. The ASF was largely missing, due to the weak density contrast between shelf and open ocean waters. Most oceanic processes occurring at present on the continental shelf, such as coastal polynyas, HSSW production and dense water formation still took place, but were confined to the continental slope, with increased intensity due to the more extreme climatic conditions at the LGM.

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## **Ostracods fauna from IODP\_374 Site U1523: a comparison with modern ones from the Western Ross Sea Area.**

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*Keywords:* Antarctica, Ross Sea, ostracods, IODP, climatic and oceanographic changes.

Ostracods, calcareous bivalve microcrustaceans, are the only metazoan organisms commonly preserved as microfossils in deep sea sediments in sufficient quantities for detailed paleoceanographic studies. Detailed investigations of modern and recent regional distribution of ostracod species from shelf, slope, bathyal, and abyssal environments indicate that their distribution is strongly influenced by the physico-chemical characteristics of water masses (e.g., temperature, salinity, nutrients, dissolved oxygen, etc.), as well as substrate type and food supply. The Quaternary Antarctic ostracod fauna is mostly composed of extant species. This appearance of most extant species during the Quaternary may suggest that rapid climate cooling during the Plio-Pleistocene triggered diversification of cryophilic ostracods. These cryophilic ostracods constitute the modern Antarctic fauna showing high endemism and only few of them are found from the South American continental shelf and the Magellan Strait. The scarce knowledge of the modern Antarctic ostracods and in particular of their relationship with environmental parameters and physico-chemical characteristics of the water masses actually represents a strong obstacle in particular for the definition and analysis of environmental, climatic and oceanographic changes that have affected older periods. For this purpose, for a possible interpretation of the environmental and climatic changes that affected the Ross Sea in particular during the Plio-Pleistocene, the ostracod associations found in ninety surface sediment samples taken during different oceanographic research cruises were analyzed. The data obtained were connected with the numerous physico-chemical data of the water masses taken since the 90's by the oceanographic research cruises organized by the National Research Program in Antarctica (PNRA) in the Western Ross Sea area. In this way we obtained the distribution (presence absence) of the ostracod modern species in the Western Ross Sea such as induced by the different oceanographic settings and environmental conditions. These results have been compared with high quanti/qualitative ostracod associations values recorded in three units recovered in the IODP\_374 Site U1523 that show an equivalent fauna to the modern sediments. So we believe which could be possible, through the comparison between modern and past ostracod associations, to provide a possible reconstruction of the complex environmental, climatic and oceanographic changes that have affected the Ross Sea during the last 3.0 Ma.

## **Paleoenvironmental and paleoclimate reconstruction of a Pleistocene (MIS 5.5) fossiliferous shallow-water deposit (Mar Piccolo, Taranto, Southern Italy)**

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*Keywords:* Last interglacial, MIS 5.5, mollusks, paleoecology, Taranto.

This work shows the preliminary results of a study conducted on two fossiliferous bulk samples (named T13 and T5), Tyrrhenian in age (interglacial MIS 5.5), collected in 1976 in a weakly cemented calcarenite outcropping along the Mar Piccolo coastline (Taranto). The study focused on the autoecology of molluscan species, selecting those with > 1% dominance (representing about 79% of the association in T13 and 82% in T5). Both paleocommunities inhabited the lower infralittoral, dominated by the biocoenosis of Fine Well Sorted Sands (SFBC), associated with species related to vegetated bottoms [biocoenoses of Photophilous Algae (AP) and of *Posidonia* Meadows (HP)]; representatives of the Heterogeneous Community (PE) suggest moderate instability conditions. As indicated by the dominant biocoenosis (SFBC), sand-related species are dominant, followed by those requiring a mixed substrate; proportions of endofauna and epifauna are similar in the two samples. Despite similarity, the two samples differ in some aspects concerning the hydrodynamics of the bottom. On one hand, T13 species indicate a relatively major energy, due to the presence of the biocoenosis of Coarse Sands under Bottom Currents (SGCF) and species of intermatte channels; moreover, the presence of gravel related taxa and the dominance of suspension feeders is detected. On the other hand, T5 shows a small percentage of taxa exclusive of the biocoenosis of Superficial Muddy Sands in Sheltered Areas (SVMC), along with some of the deeper biocoenosis of Coastal Terrigenous Muds (VTC); mud related species are more abundant and detritus-feeders dominate. It is also of note the presence in T13 (< 1%), of species referable to the so called “Senegalese fauna”, such as *Persististrombus latus*, *Conus ermineus* and *Cardita rufescens*, which are not detected in T5. In conclusion, both samples are indicative of a similar paleoenvironmental setting, within a locally vegetated infralittoral sandy bottom, characterized by a lateral transition from a relatively high-energy level (T13) to more sheltered bottom conditions (T5). Moreover, the subtropical to eurythermal character of all the identified bivalves along with the presence of Senegalese taxa, suggest for such MIS 5.5 interglacial calcarenite a relatively warmer climate compared to the present, as the mean of the sea-water range of the tolerance temperature of *P. latus* of circa 23° C is higher than the present-day yearly mean of temperature, that is circa 18° C in the interval 1918 -2004. Geochemical studies on skeletons of key species are underway to better define this aspect.

## The long-term relationship between sea-level change and sedimentation

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*Keywords:* sea-level change, glacial isostatic adjustment, stratigraphy, sedimentation, numerical modelling, data assimilation.

Sea-level rise (SLR) is one of the most important consequences of global warming and carries significant repercussions on coastal human settlements and natural ecosystems. Global SLR research aims at solving the so-called “sea-level budget” over the last few glacial-interglacial cycles. Global-scale research efforts then provide the forcing and boundary conditions for regional-scale glacial- and hydro-isostatic adjustment (GIA) modelling. At that scale, sediment isostasy and compaction (SIC) becomes an important additional factor that has to be implemented in the modelling, through data intake and adapted algorithms. Regional sedimentation varied greatly in rates and amounts and locations between glacial and interglacial times, partly controlled by SLR and GIA movements but also independently. By accounting for sedimentation through the combination of mapping knowledge (data assimilation) and deterministic geophysical modeling, the magnitude of local SIC vs. regional GIA patterns can be revealed. In this work the contribution of GIA-driven RSL changes in drawing the architecture of stratigraphic sections is investigated by means of a novel numerical modeling approach. The latter consists in the full coupling between a GIA model, which is based on the Sea Level Equation, and two sedimentation models that are based, respectively, on (i) fuzzy logic and on (ii) the numerical solution of the heat transfer (diffusion) equation. Among the several variables that regulate marine sedimentation, changes in bathymetry and distance from shore and ice-sheet margin are directly linked to the gravitationally self-consistent RSL changes that are driven by GIA. The latter is also influenced by the load of the sediments that contribute to solid Earth and gravitational perturbations. The proposed algorithm, therefore, handles the biunivocal relationship between RSL changes and sediment loading in a synergistic manner. The model is used here to reconstruct the last two glacial-interglacial transitions and highlight the differences in the North Sea (intermediate field), Adriatic Sea (ice distal) and Ross Sea (ice proximal). Preliminary results show that the reconstructed ice-proximal stratigraphic sections, either based on fuzzy logic or diffusion, are significantly affected by the GIA process and that the eustatic approximation should be discarded. Also, SIC is currently causing local subsidence and erosion in the proximity of river mouths where modern sedimentation rates cannot keep pace with SLR. This is a significant result for our understanding of centennial-millennial coastal plain development and habitat evolution, and for evaluating anthropogenic vs. natural sedimentation.



## Temperature vs extinction events: the case of Rhaetian peritidal carbonate succession from westernmost Tethys (Sicily)

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Keywords: biodiversity, End Triassic Extinction, paleotemperatures,  $\delta^{18}\text{O}$ , biocalcification crises, Sicily.

A biodiversity crisis was observed in the benthic community from a latest Triassic carbonate platform of western Tethys. The studied succession, i.e. Mt Sparagio section in NW Sicily, consists of a continuous Upper Triassic to Lower Jurassic peritidal carbonate succession organized in shallowing upward cycles. The Upper Triassic horizons can be sub-divided into two informal units on the base of the benthic fossils assemblage: at the base the Unit A (thickness about 111 m) consists of a high diverse fossiliferous assemblage comprising very large megalodontoids specimens (up to 40 cm); Unit B (about 179 m) shows a reduction of biodiversity with the occurrence of rare and small megalodontoids (Conchodon?) up to 15 cm in size. Both units are Rhaetian in age as indicated by the presence of large tested specimens of the benthic foraminifer *Triasina hantkeni*. The top of Unit B is marked by an oolitic level, and records the total disappearance of the Triassic benthic fossil assemblage. Upward, the subtidal members of peritidal cycles (Unit C) show the presence of an oligotypic assemblage with *T. parvovesiculifera*, which represents a survival zone, followed in turn by a gradual recovery of the Lower Jurassic benthic community (e.g. *Siphovalvulina* sp.).

A negative excursion of  $\delta^{18}\text{O}_{\text{carb}}$ , corresponding to an increase in temperature, matches the biodiversity reduction between Unit A and Unit B. This episode correlates the Initial Carbon Isotopic Excursion already individuated in this section and related to the first pulse of the CAMP volcanic activity. A second change in temperature that is characterized by a positive excursion of  $\delta^{18}\text{O}_{\text{carb}}$  matches the total extinction of the Upper Triassic benthic community. These data well fit with the environmental parameters of the modern tropical shallow water platform (T-factory). In particular, the sea surface temperature (SST) of a T-factory range from 18 °C to 30.5 °C representing respectively the minimum SST for the carbonate factory persistence and the maximum SST that a T-factory can tolerate.



## Ross Sea snapshots from the past – GLEVORS Project indirect and direct records

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*Keywords:* Antarctica, Ross Sea, continental shelf, post-LGM environment, micropaleontology.

Geophysical/geological data integration contribute to constrain the reconstruction of the deglaciation patterns imprinted on the seafloor (Anderson et al., 2018; Bart et al., 2020; Prothro et al., 2020). The Northern Drygalski Basin (Ross Sea western coast) shows a subglacial landscape tectonically and ice drainage controlled. Seismo-stratigraphic architectures, related to the fluctuations of the East Antarctic Ice Sheet, allow to interpret the glacial-deglacial sediment depocenters and the Grounding Zone Wedges in this area. Sedimentological, micropaleontological and geochemical analysis on two GLEVORS (Glacial Evolution in the north-western Ross Sea, offshore North Victoria Land – Antarctica) Project Cores GC01 and GC02, result basic for a reliable geomorphic reconstruction in a context where ice landforms and bedforms were shaped and where grounding lines and melt-water processes took place. The sediment cores, considered as important time-snapshots can provide a chronostratigraphic control on the past marine-based ice-sheet vulnerability and retreat and on the records of the ice streams draining catchments, the post-LGM biological, cryosphere/atmosphere and oceanographic processes (Kim et al., 2018; Post et al., 2020; Smith et al. 2020).

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## **Environmental and Oceanographic Conditions at the Continental Margin of the Central Basin, Northwestern Ross Sea (Antarctica) since Last Glacial Maximum**

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*Keywords:* diatoms, micropaleontology, sedimentology, cryptotephra, Central Basin, Western Ross Sea, Antarctica.

Over the last few decades, different researches have led to important advances in our understanding of late Quaternary Antarctic Ice Sheet (AIS) behavior. However, the continental shelf margin remains still poorly investigated. To address this issue, we aim to increase the knowledge of the last glacial/deglacial dynamics in the Central Basin (slope-basin system) using a multidisciplinary approach, including sedimentological, micropaleontological, and tephrochronological analyses performed on marine sediments cores. Based on grain size clustering and the sortable silt data, together with diatom, silicoflagellate and foraminifera assemblages, we recognize three stratigraphic units. Unit 1 (24-17 ka BP) documents the influence of the ice shelf calving zone vicinity, Unit 2 (17-10.2 ka BP) represents the progressive retreat of the ice shelf due to Circumpolar Deep Water inflow, and Unit 3 (10.2 ka BP-present) corresponds to the establishment of seasonal sea ice with a strengthening of bottom currents. The dominant and persistent process is the sedimentation controlled by contour currents, which tend to modulate intensity in time and space. The study also allowed us to document the presence of a primary volcanic ash layer dated 22 ka BP correlated with the explosive activity of Mount Rittmann. This study has been conducted in the framework of the STREAM Project (Late Quaternary evolution of the ocean-ice sheet interactions: the record from the Ross Sea continental margin, Antarctica) funded by the Italian Ministry of Foreign Affairs and International Cooperation and the National Research Foundation of Korea.

## **Bottom current control on sediment deposition between the Iselin Bank and the Hillary Canyon (Antarctica) since the late Miocene: an integrated seismic-oceanographic approach**

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*Keywords:* Contourite drift, seismics, oceanography, along Slope Current.

In this paper we analyze how oceanic circulation affects sediment deposition along a sector of the Ross Sea continental margin, between the Iselin Bank and the Hillary Canyon, and how these processes evolved since the Late Miocene. The Hillary Canyon is one of the few places around the Antarctic continental margin where the dense waters produced onto the continental shelf, mainly through brine rejection related to sea ice production, flow down the continental slope and reach the deep oceanic bottom layer (Gales et al., 2021). At the same time the Hillary Canyon represents a pathway for relatively warm waters, normally flowing along the continental slope within the Antarctic Slope Current, to reach the continental shelf. The intrusion of warm waters onto the continental shelf produces basal melting of the ice shelves, reduces their buttressing effect and triggers instabilities of the ice sheet that represents one of the main uncertainties in future sea level projections. For this study we use seismic, morpho-bathymetric and oceanographic data acquired in 2017 by the R/V OGS Explora. Age models from two drilling sites (U1523 and U1524) of the Integrated Ocean Discovery Program (IODP) Expedition 374 (McKay et al., 2019). Oceanographic data, together with a regional oceanographic model, are used to support our reconstruction by showing the present-day oceanographic influence on sediment deposition. Regional correlation of the main seismic unconformities allows us to identify eight seismic sequences. Seismic profiles and multibeam bathymetry show a strong influence of bottom current activity on sediment deposition since the Early Miocene and a reduction in their intensity during the mid-Pliocene Warm Period. Oceanographic data and modelling provide evidence that the bottom currents are related to the dense waters produced on the Ross Sea continental shelf and flowing out through the Hillary Canyon. The presence of extensive mass transport deposits and detachment scarps indicate that also mass wasting participates in sediment transport. Through this integrated approach we regard the area between the Iselin Bank and the Hillary Canyon as a Contourite Depositional System (ODYSSEA CDS) that offers a record of oceanographic and sedimentary conditions in a unique setting. The hypotheses presented in this work are intended to serve as a framework for future reconstructions based on detailed integration of lithological, paleontological, geochemical and petrophysical data.

Gales J., Rebesco M., De Santis L., Bergamasco A., Colleoni F., Kim S., Accettella D., Kovacevic V., Liu Y., Olivo E., Colizza E., Florindo-Lopez C., Zgur F. & McKay R. (2021) - Role of dense shelf water in the development of Antarctic submarine canyon morphology. *Geomorphology*, 372, 107453.

McKay R., De Santis L., Kulhanek D., Exp. 374 Scientists (2019) - Ross Sea West Antarctic Ice Sheet History. *Proceedings of the International Ocean Discovery Program Expedition 374*.

**S20.**

**Resilience of oceanic ecosystems preserved in the geological  
record**

*CONVENERS AND CHAIRPERSONS*

*Giulia Faucher [Università degli Studi di Milano - Statale]*

*Mariano Parente [Università degli Studi di Napoli Federico II]*

*Marco Romano [Sapienza Università di Roma]*

## **Learning from the present to inform the past and future of coccolithophore calcification**

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*Keywords:* coccolithophores, ocean acidification, environmental stress.

Coccolithophores are an important group of marine phytoplankton. Their unique feature is the ability to form a calcareous shell - the coccosphere - composed of several individual plates (coccoliths) attached to the cell surface. Coccolithophores are sensitive to environmental change, which is reflected in their variable species diversity, cell abundance, and coccolith morphology observed in the paleorecord since the Triassic.

In this seminar I will present results from laboratory and field studies where coccolithophores were exposed to environmental stress (mainly ocean acidification). I will utilize the outcomes of these studies to derive predictive understanding, which may help us (i) to understand observed changes of coccolithophore abundance in the past, and (ii) better project their future in a rapidly changing climate. In this context, I will link our understanding of coccolithophore responses to perturbation with ecological theory. I hope to provide compelling arguments why ecological concepts should be considered when interpreting past, and predicting future, abundance of coccolithophores.

## **Preliminary attempt to assess the resilience of shallow-water communities through biodiversity patterns of Neotethys Paleogene larger foraminifera and corals**

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*Keywords:* climate changes, larger foraminifera, corals, Paleogene, biodiversity.

This contribution is part of ongoing researches aimed to analyse the diversity of shallow-water benthic communities as concerns the larger foraminifera (LF) and scleractinian corals.

In the last year we collected a huge amount of data about the distribution of both larger foraminifera and corals in space and time in order to produce more complete as possible databases and perform analysis of diversity at large scale, by including all the taxa described and cited from the Paleogene of the Neotethys. This work required time-consuming researches and critical revisions of numerous published papers, that often have called for taxonomic comparison and systematic re-evaluation.

The Paleogene, as a period of important climate changes, with special regards to hyperthermal events, plays an important role in understanding the response of shallow-water taxa and their resilience capacity after sudden crisis events.

As concerns LF our preliminary data underline a first generic radiation during the Paleocene, followed, after the PETM crisis, by a rapid specific diversification with special regards to alveolinoidea and nummulitoidea. An increase in biodiversity is recorded during the EECO, i.e., Shallow Benthic Zones (SBZ) 10 and 11, followed by a rapid but not sudden decline. The last great diversification of LF, marked particularly by the Nummulites species, occurred in the Bartonian SBZ17, roughly corresponding to the MECO. After this events LF communities began their decline culminating in the lower Oligocene. A slight recovery has been recorded in the late Chattian due especially to the diversification of the rotaloidean family Miogypsinidae.

Corals, instead, seem to show a decrease in diversity during the Selandian, followed by a generic and specific variability during the Eocene, with peaks in species diversity during the Ypresian and the Priabonian, thus revealing their resilience after the EECO and MECO hyperthermal events. At the end of the Paleogene, the corals generic diversity reaches its maximum peak in the Chattian, roughly corresponding to the LOWE.

Our datasets, when completed, will allow us to better understand the relationships among the investigated shallow-water taxa, their diversification through the whole Paleogene and their response to the major climatic events.

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## How coccolith size changed in response to paleoenvironmental variations during the Early Aptian to Late Albian?

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**Keywords:** Cretaceous, calcareous nannofossils, morphometrics, OAE 1b.

In the geological record, calcareous nannofossils are intensively studied, because they are important palaeoecological tracers. Today, as in the past, coccolithophores are really sensitive to environmental changes. So, their growth and calcification rates could be influenced by different factors such as temperature, carbonate chemistry and/or nutrient content (i.e, Erba et al., 2010; Wulff et al., 2020). The variations in nanoplankton abundance, shape and/or coccolith size could give information of past ocean-atmosphere conditions including the amount of CO<sub>2</sub> exchange between the ocean and the atmosphere.

For this research the time interval selected is the Early Aptian to Late Albian (ca. 121-100 Ma) which was characterized by important climatic and paleoenvironmental changes including a cooling event in the early late Aptian, and two “Ocean Anoxic Events”, namely the OAE 1a and OAE 1b. Particularly, the focus is on the Aptian/Albian boundary and the Oceanic Anoxic Event 1b. The whole study interval was selected because morphometrics analyses on *Biscutum constans* from the Western Tethys documented relatively small sized specimens in the early late Aptian (Bottini & Faucher, 2020), followed by average size increase after OAE 1b. Here, we conduct new morphometries on species with particular affinities in temperature or fertility such as *Watznaueria barnesiae* (oligotrophic species), *Rhagodiscus asper* (warm water species), *Zeugrhabdotus erectus* and *Biscutum constans* (mesotrophic species).

The aim of the study is to a) see if there are any dimensional variations in different species other than *B. constans*; b) investigate if the species responded to paleotemperature and paleofertility changes with size variations and c) detect if the coccolith size justifies a decrease in nanoplankton calcification and how this possibly influenced the total carbon budget. Thus, in order to reach these objectives, we studied samples from ODP Site 1049 (Proto-North Atlantic) and the Piobbico core (Umbria-Marche Basin, central Italian Apennines) and we have correlated new morphometrics data with the nannofossil abundance, temperature and fertility index.

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Wulff L., Mutterlose J. & Bornemann A. (2020) - Size variations and abundance patterns of calcareous nannofossils in mid Barremian black shales of the Boreal Realm (Lower Saxony Basin). *Marine Micropaleontology*, 101853.



## **First evidence of the Oceanic Anoxic Event -2 in the shallow-water carbonates of the Friuli Carbonate Platform: geochemical and sedimentological data**

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*Keywords:* OAE-2, Oceanic Anoxic Event, shallow water carbonate platform, mid-Cretaceous, Cenomanian-Turonian.

The Cenomanian–Turonian Oceanic Anoxic Event 2 (OAE-2) represents a major perturbation of the global carbon cycle associated with the extensive deposition of organic carbon-rich deposits (black shales) in the oceanic basins, worldwide. Numerous studies have suggested that enhanced volcanic activity at mid-oceanic ridges and large igneous province (LIP) eruptions may have acted as potential trigger mechanisms of this event. These phenomena caused excess CO<sub>2</sub> degassing and a consequent dramatic temperature increase in the oceans and atmosphere. Although the geochemical, sedimentological and paleontological changes throughout the OAE-2 are well-known in basinal deposits, the shallow-water carbonate counterpart is still poorly investigated. The OAE-2, however, strongly impacted both deep and shallow-water ecosystems. The limited information on the expression of the OAE-2 in carbonate platforms represents a critical gap in our understanding of ecological responses to abrupt paleoenvironmental/paleoclimatic changes in the mid-Cretaceous, given that shallow shelves accounted for a significant part of the global ocean biological productivity and carbonate production.

In this work we present new high-resolution geochemical and sedimentological data across the OAE-2, based on bivalve shells and bulk rock material from a well exposed upper Cenomanian – lower Turonian section, in the carbonate successions of the Friuli Carbonate Platform (FCP) cropping out in the Karst area, near the city of Gorizia. Biostratigraphy and carbon-isotope stratigraphy were used to establish a precise stratigraphic dating and for high resolution correlations with coeval shallow-water and reference open-ocean sections. Sr-isotope data, Hg concentration and other geochemical proxies have been used to highlight possible evidence of volcanic activity and changes in weathering and to evaluate paleoenvironmental conditions on the FCP during the OAE-2. Results highlight that, during the event, the FCP underwent major biotic and geochemical changes that these fluctuations can be compared to those occurring in coeval carbonate platforms of the Tethys during the OAE-2.

## From the Early Pleistocene to the Recent: how is *Xenophora crispa* biomineralization varied?

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Keywords: Early Pleistocene, shell microstructure, cooling.

The genus *Xenophora* comprises species of marine gastropods, known from the Cretaceous and still living today, which have the ability to form their shells agglutinating objects with different origins, from other shells to bio- or lithoclasts. Different agglutination potentials are shown by species of *Xenophora*, from species lacking attachments to others completely covered, as the case of the Mediterranean *Xenophora crispa* (König, 1825).

Shell sections of fossil (Early Pleistocene, Arda and Stirone Rivers, Italy) and recent specimens (Mediterranean Sea, Spain) of *X. crispa* were here analyzed at the Scanning Electron Microscope (SEM) and powders, collected from different parts of the shell, at X-Ray Diffraction (XRD), in order to characterize in detail the microstructure and the mechanisms, function and behaviour of the agglutination in the same species through time, in this case over about 2 millions of years. Also, as the Arda and Stirone River sections were deposited during the Early Pleistocene, this research allows to examine if and how these parameters varied during a climate change. Indeed, the Early Pleistocene was a time interval characterized by several climatic oscillations linked to glacial/interglacial cycles and the Mediterranean area was strongly affected by these climatic changes showing in marine environment a progressive climatic cooling.

This study shows that the functional purpose of the agglutination in *X. crispa* may be related to a snowshoe strategy to successfully colonize muddy substrates, coupled with tactile and olfactory camouflage. Indeed, this species secretes in the columella and peripheral edge of both fossil and recent specimens a less dense and a more organic rich calcitic fabric, possibly to lighten the shell thickest parts in order not to sink in soft sediments and to facilitate the shell raising from the substrate to create a protected feeding area. This behaviour and the shell microstructure seem to have been maintained by *X. crispa* over 2 My time span, thus allowing to suppose that this species did not suffer the climatic cooling of the Early Pleistocene.

## Evidence of Tethyan calcareous plankton dwarfism across the ETM2

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**Keywords:** ETM2, planktic foraminifera, dwarfism, calcareous nannofossils, biolimiting metals, environmental perturbations.

Here we present an integrated calcareous plankton and geochemical record from the Tethyan Terche and Madeago sections (NE Italy), deposited in a middle-lower bathyal setting. These sections record a negative Carbon Isotope Excursion corresponding to Eocene Thermal Maximum 2 (ETM2, ~54 Ma). Our planktic foraminiferal and calcareous nannofossil records show significant, though temporary, changes in both sections across this event. No significant dissolution occurred that could have affected the assemblages. Warm index surface-dweller *Acarinina* increased while of the deeper-dweller chiloguembelinids and subbotinids declined in abundance. A test reduction of up to 50% compared to pre-event sizes for both surface- and deeper dwellers planktic foraminiferal is particularly marked at Madeago. While symbiont bleaching can reduce growth, both symbiont and asymbiotic planktic foraminifers were affected at the same scale in our sections at the ETM2, and hence not a likely cause of the size reduction. The enhanced surface remineralization of organic matter due to warming may have reduced the food input at the thermocline, thus contracting the deeper ecological niches. The calcareous nannofossil assemblages provide evidence of increased surface water eutrophy during the ETM2. The increase in small placoliths *Toweius* and *Ericsonia* may indicate that dwarfism also affected nannofossil assemblages, though to a lesser degree. We thus hypothesize that the ETM2 perturbation impacted the entire upper water column possibly changing stratification and niche spaces.

To establish whether the observed dwarfism was related to environmental stressors which are not commonly linked to the ETM2 climatic perturbation, we quantified the Hg (ppb), TOC (wt%) and Hg/TOC (ppb/wt%) geochemical proxies through our sections. Results show an increase in Hg in both sections at the base of the ETM2. We attribute this increase to coeval submarine igneous events that might have introduced biolimiting metals, which changed plankton productivity and possibly affected test size. However, we cannot exclude reworking of the metal because we record an increase in sedimentation rate and nannofossil rework at the ETM2. We suggest that the plankton dwarfism, here documented for the first time across the ETM2, could be the result of the coupled effect of increase in biolimiting metals and changes in the physicochemical structure of the upper water column.

## Living and Fossil Coccolithophores: a tool to understand past and future climate changes

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Keywords: climate change, marine carbon cycle, coccolithophore cultures, micropaleontology, Marine Isotope Stage 5.

The increasing effects of anthropogenic carbon dioxide (CO<sub>2</sub>) emissions on climate change pressure the scientific community to provide accurate predictions of the future consequences of these variations. The oceans and marine organisms are strongly affected by climate and CO<sub>2atm</sub>, but they also produce pivotal feedback on climate. Thus, studying the marine carbon cycle is crucial to understand the drivers regulating the past, present, and future evolution of climate. Among marine biota, coccolithophores, a group of calcifying marine phytoplankton, play a key role in the ocean carbon cycle at various timescales providing pivotal information on the oceans' capacity towards CO<sub>2</sub> buffering. They are also particularly sensitive to environmental variations making them excellent climate proxies. In this study, experimental cultures of the species *Helicosphaera carteri* cultivated in turbidostats under CO<sub>2</sub>-controlled conditions were compared to the fossil coccolithophore assemblage at the International Ocean Discovery Program (IODP) Site U1501 (South China Sea). The combination of paleontological and culture-derived data can improve predictions of the state of biodiversity in the future under varying climate change scenarios. *Helicosphaera carteri* cultures were grown under 425 ppm CO<sub>2</sub>, a level consistent with the best-case scenario predicted by the Intergovernmental Panel on Climate Change (IPCC), the Representative Concentration Pathway (RCP) 2.6 (IPCC, 2014). The selected time interval for studying the fossil coccolithophore assemblage belongs to Marine Isotope Stage 5 (130-70 kyr), a geological interval considered as an analogue for modern warming. Through the study of the fossil record, we identified significant changes to the coccolithophore community during the warmest substages of MIS5, i.e. MIS5e. Site U1501 recorded a significant peak in coccolithophore absolute abundance related to increased productivity during MIS5e, and consequently, the highest coccolith-derived carbonate contribution to bulk calcium carbonate of the last 300 kyr. Data from cultures indicated the resilience of *H. carteri* towards high CO<sub>2</sub> through the maintenance of well-preserved coccoliths. However, the growth rate, despite being constant, was slightly lower than the control culture, indicating a decreased contribution to calcite production/export under high CO<sub>2</sub> levels. The results suggest coccolithophores may play an important, but shifting role in carbon sequestration in a warmer world. Further, this comparison contributes to improving our understanding of the potential effects of anthropogenic climate change on oceanic primary producers like coccolithophores.

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IPCC (2014) - Climate Change, 2014. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

## Mg/Ca Paleotemperatures changes at the demise of planktic foraminiferal genus *Morozovella* across the Early Eocene Climatic Optimum (Site 1263, Southern Atlantic Ocean)

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**Keywords:** planktic foraminifera, Early Eocene Climatic optimum, Mg/ Ca paleotemperatures, laser ablation, Morozovellid decline.

We present here data on changes in Mg/Ca derived paleotemperatures from the southern Atlantic Site 1263 across the Early Eocene Climatic Optimum (EECO; ~53-49 Ma). The EECO, that records the peak of Cenozoic warmth, and possibly of the CO<sub>2</sub> pressure (e.g., Zachos et al., 2001, *Science*; Anagnostou et al. 2016, *Nature*; Inglis et al., 2020 *Clim. Past*), induced climatic and paleoceanographic changes that significantly impacted planktic foraminiferal assemblages. The main change, recorded from several sites (Atlantic and Pacific Oceans, Tethys) is the permanent and markedly declined in abundance and diversity of the mixed-layer dwelling symbiotic bearing genus *Morozovella* coupled with the increase of genus *Acarinina* (Luciani et al., 2016; Luciani et al. 2017a; Luciani et al. 2017b; D'Onofrio et al., 2020). This decline occurred at the EECO beginning, close to the carbonate isotope excursion known as 'J event' (~53 Ma). In addition, a reduction in morozovellid test-size occurred across EECO as recorded from Atlantic ODP sites 1051, 1258 and 1263. Several potential stressors may explain both the reduced size and the permanent morozovellid decline. These include algal photosymbiont inhibition (bleaching), increase in temperature, decrease in pH and/or calcite saturation state. Even though a bleaching test at Site 1051 revealed only a transient reduction of algal-symbiont relationships just after the morozovellid abundance decline (Luciani et al., 2017a), a general reduction in  $\delta^{13}\text{C}$  gradient (~ 0.5 ‰) between morozovellids and the thermocline dweller *Subbotina* spp. through the EECO is recorded from the Atlantic sites. This suggests that the former group became less reliant on photosymbionts and/or may have moved to slightly deeper depth in the mixed-layer. Even though a link with the EECO perturbation is evident, the driving causes of the recorded modifications are still unknown. Detailed paleotemperatures across the observed changes were lacking. We therefore obtained Mg/Ca derived paleotemperatures from Site 1263 through Laser Ablation, a method widely applied. Preliminary Mg/Ca data reveal that *Morozovella* crater and *M. subbotinae* record a major warming across EECO greater than that of *Acarinina coalingsensis* and *A. soldadoensis*. Although the exact causes of photosymbiont bleaching can be manifold, increased temperature is considered a primary cause of bleaching in present tropical larger benthic foraminifera (e.g., Hallock, 2000). The higher rise in temperature recorded by morozovellid may explain the reduced symbiotic relationship and suggests one possible reason for their reduction in abundance and size, even though other potential stressor such as pH decrease should be explored. We record from Site 1263 also a temperature increase at the thermocline that may be one of the causes explaining the drop in abundance of subbotinids and chiloguembelinids at the EECO.

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## The impact of Early Eocene Climatic Optimum Change on coiling direction of planktic foraminifer *Morozovella* from the Atlantic Ocean: quantitative and stable isotope data

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Keywords: Planktic foraminifera, Early Eocene Climatic Optimum, Morozovellid coiling direction, Stable isotopes.

Here we present new insight on the relationship between early Eocene carbon-cycle changes, abundance and coiling direction of the trochospiral planktic foraminiferal genus *Morozovella*. We investigated the coiling direction within *Morozovella* populations at three widely separated locations in the Atlantic Ocean, Ocean Drilling Program sites 1051, 1258 and 1263, which span the EECO (~49-53 Ma), the interval when Earth surface temperatures and atmospheric pCO<sub>2</sub> reached their Cenozoic maximum (e.g., Zachos et al., 2001; Anagnostou et al. 2016). Coiling direction is a key characteristic of trochospiral planktic foraminifera. However, although modifications in the coiling direction may reflect important changes in evolution or environment, they remain scarcely discussed. The symbiont-bearing surface-dweller planktic foraminiferal genus *Morozovella* was a clear target because it dominated tropical-subtropical early Paleogene assemblages, but its abundance abruptly and permanently declined at the EECO beginning, close to the carbon isotope excursion known as the J event (~53 Ma) (Luciani et al., 2016; Luciani et al., 2017a; Luciani et al., 2017b; D'Onofrio et al., 2020). Our results demonstrate that multiple morphologically defined species of *Morozovella* display a dominant dextral coiling preference during the interval preceding the EECO. However, the *Morozovella* morphospecies switched from dextral (DX) to sinistral (SN) coiling within ~ 200 kyr after the carbon isotope excursion known as K/X event (~52.8 Ma). In addition, we provide new stable carbon and oxygen data on SN and DX morphotypes collected at different time intervals below and above the major coiling shift, in order to provide information on the habitat and/or ecological behaviour of the two morphotypes. Results show that SN morphotypes typically have lower δ<sup>13</sup>C values. The dominance of SN morphotypes that survived, though in low abundance, at the expense of DX forms within EECO, coupled with the lower δ<sup>13</sup>C signatures of the former, suggests that the SN morphotypes were less dependent on their photosymbiotic partnerships and thus possibly able to better tolerate water stressors occurring during the EECO. These evidences strongly suggest a causal relationship to environment and possibly to temperature increase. However, the observed SN and DX morozovellids coiling variations can be a genetically heritable characteristic that lies within cryptic speciation across multiple morphologically defined species. Our present data cannot validate or disprove any of the possible scenarios. To support the ecophenotypic response or to disprove it we need a more comprehensive knowledge of the EECO in terms of environmental change in surface waters during the recorded coiling switch. Our records further highlight that the recorded coiling variations might provide a new biostratigraphic tool for correlation.

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## **The record of the end-Triassic mass extinction in the Southern Apennines carbonate platform (Italy)**

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*Keywords:* Triassic-Jurassic boundary, mass extinction, carbon isotope stratigraphy, ocean acidification, Western Tethys.

The end-Triassic mass extinction is one of the big five of the Phanerozoic. It is associated with severe perturbations of the global carbon cycle, recorded by the worldwide occurrence of a series of negative carbon isotope excursions (CIEs) in both the inorganic and organic marine carbon record. The massive injection of isotopically light CO<sub>2</sub> into the atmosphere/ocean system from the paroxysmal volcanic activity of the Central Atlantic Magmatic Province has been invoked as the cause of the CIEs, of abrupt climate change, ocean acidification and mass extinction.

In many areas of the Tethyan ocean, carbonate platform sedimentation was terminated around the T-J boundary. In the resilient carbonate platforms that were able to survive the crisis (e.g. the southern Apennine carbonate platform in southern Italy), fossiliferous limestones with corals, sponges, chetetids, large megalodontid bivalves and rich and diverse benthic foraminiferal associations, change abruptly into unfossiliferous peritidal and/or oncolitic-oolitic limestones around the T-J boundary. We have sampled in detail a 244m thick section exposed near the village of Valle Agricola, in the Matese Mts, about 65 km north of Naples (southern Italy). The lower interval (0-205m) is made up of peritidal cycles, consisting mainly of wackestone-packstone with benthic foraminifers and dasycladalean algae and wackestone to floatstone with large megalodontids, corals and chetetids, capped by microbial laminites and supratidal facies with microkarstic cavities. The upper interval (205-244m) is entirely made up of unfossiliferous grainstone-rudstone with ooids, oncoids and intraclasts. We use carbon isotope stratigraphy, tied to benthic foraminifera biostratigraphy, to correlate the Valle Agricola section with other previously studied sections in the southern Apennines, including the Monte Cefalo carbonate platform section and the Pignola-Abriola section in the Lagonegro basin, which has been recently proposed as the GSSP candidate for the base of the Rhaetian. These correlations allow us to elucidate the sedimentary dynamics and evolution of the southern Apennine carbonate platform and of the adjoining Lagonegro Basin across the latest Norian to earliest Hettangian time interval. We then perform a high-resolution correlation with the classical Val Adrara/Italcementi quarry section in the Lombardy Basin, and with other reference sections like the base of Hettangian GSSP of Kuhjoch (Austria) and the St Audrie's Bay section (UK), aiming at interpreting the evolution of the Apennine carbonate platform in the framework of the end-Triassic events. Finally, we attempt using stratigraphic changes in minor and trace elemental concentration, measured with a portable XRF device, to build a high-resolution orbital cyclostratigraphy for the Valle Agricola section.



## Brachiopods from Iran and their record of the end-Permian events

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Keywords: biotic change, brachiopods, Permian.

Brachiopods, which are marine, benthic, low-metabolism and physiologically unbuffered organisms with a calcite shell, are good tools for recording the dramatic biotic response to the end-Permian events: volcanism, global warming and ocean acidification. Upper Permian brachiopods from Iran (mainly from Julfa and Alborz Mts. sections) have already proved to be good recorders of extreme warming and acidification occurring at the end of the period, based on their stratigraphic distribution, shell microstructure, and geochemistry analyses (e.g. Garbelli et al., 2017).

Here, we provide additional data on the brachiopod shell microstructure and distribution along the Abadeh section, Central Iran (Taraz et al., 1981), one of the most well known section, which consists of a continuous marine succession spanning the Late Permian to Early Triassic time interval, from the Abadeh Fm. to the Hambast Fm. and the Elikah Fm.

The newly studied brachiopods comprise more than 400 specimens belonging to 13 genera and 29 species, dominated by the order Productida and Athyridida. An analysis of the distribution of fibrous fabric vs. laminar ones show that the former increase in abundance in the upper part of the sections, from the base of the conodont zone *Clarkina transcaucasica* to become the only occurring taxa at the top of the *Paratirolites* Limestone.

A correlation between the Abadeh (Central Iran) and the Julfa section (NW Iran) (Ghaderi et al., 2014) has been obtained based on brachiopod biozonation. In both sections the topmost part of the *Paratirolites* Limestone is characterized by the occurrence of *Paracrurithyris pygmaea*, a disaster taxon, one of the few species of marine organisms that, in the fossil record, has been found before, during and after the extinction interval. The fibrous shell of this species is one of the best recorder of the ocean acidification at the end of the Permian (Jurikova et al., 2020).

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**S21.**  
**Holocene climate**

*CONVENERS AND CHAIRPERSONS*

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## Oxygen minimum zone formation in the Western Mediterranean sea associated to last deglacial melting and sea level rise

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**Keywords:** Mediterranean Thermohaline Circulation, oxygen minimum zone, Sapropel, Organic Rich Layer, Last Deglaciation.

Mediterranean thermohaline circulation (Med-THC) is driven by different overturning cells located in both the Eastern and Western basins. The Levantine basin is the main source of intermediate waters which contribute to the formation of deep water masses in both the E and W basins. Climate conditions are closely linked to this Med-THC system, and paleoceanographical evidence reveal major changes in these two main Mediterranean regions. Deglacial climatic/oceanographical changes led into a weakening of the W-Med deep convection cell that promoted the formation of the so-called last Organic Rich Layer (ORL1) in the Alboran Sea, which pre-dated the formation the last sapropel deposition (S1) in the E-Med. Here we present a novel application of U/Mn ratios from the diagenetic coating of foraminifera as a proxy for deep water dissolved oxygen content and measured in a set of sediment cores covering a broad range of water depths mostly from the W-Med. The results confirm that the Mediterranean surface waters freshening associated with the last Heinrich melting was responsible for a major weakening of the W-Med-THC that in turn decreased the oxygen content at least below 900m. Reduced water renewal became more pronounced during the Bolling-Allerod interstadial (15 ka BP) leading to the onset of the ORL1 formation in the Alboran Sea. But interestingly, the new data reveal the formation of an oxygen minimum zone at intermediate depths (900m) which re-ventilated during the Younger Dryas Stadial (YD). While the W deep basin apparently never reached such low oxygen conditions, some degree of disoxic deep water conditions occurred in the Alboran Sea (1800m), reaching maximum values during the YD, and maintained until the onset of the Holocene (11.3 kyr BP). That deep re-ventilation phase predates the defined end of the ORL (9 kyr) pointing to primary productivity as the main driver for this latest phase of ORL formation. These new results also support that S1 formation started when deep convection in the W-Med was fully reinstalled, highlighting an antiphase behavior between the two basins. Nevertheless, the identification of this intermediate oxygen minimum zone, and its earlier YD re-ventilation phase, open new questions on the potential role of E-Med source waters controlling these changes in the intermediate thermohaline circulation of the W-Med.

## Exploring climate and environmental changes in Sardinia around the end of the Nuragic Era

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Keywords: Holocene, palaeoclimate, palaeoenvironment, speleothems, Nuragic Era.

In Sardinia, precisely dated Holocene climate and environmental records are derisory. Indeed, availability of lacustrine sediments is scarce, because this Island has one natural relatively large lake only. Accordingly, the most comprehensive Holocene lake-based climate reconstruction, spanning the last 8000 years, has been published only recently (Pedrotta et al., 2021). However, the authors admit a low reliability of their age model to the top of the sequence, around the last ~2500 years. Considering the location of Sardinia at the center of the Western Mediterranean basin, this gap of knowledge is unfortunate, given the number of studies carried out in nearby continental/marine areas. Additionally, the lack of palaeoclimate/environmental information still hampers a thorough comprehension on the evolution of ancient populations, including the possibly most sophisticatedly advanced Bronze and Late Iron Age culture in Europe: the Nuragic civilization (~1700-500 BC).

An efficient way to retrieve palaeoclimate information in Sardinia is through speleothems, considering that: 1) the Island counts almost 4000 caves; and 2) for pre-Holocene times, we have already reported the reliability of Sardinian speleothems as powerful records of past climates (Columbu et al., 2017; 2019). This work presents the first speleothem-based Holocene environmental reconstruction from Sardinia, by reporting the preliminary <sup>230</sup>Th dating, stable isotopes ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) and petrographic results from 5 stalagmites. Samples were recovered in Suttaterra de Sarpis cave (Urzulei), which is strategically located less than 1 Km from Or Murales Nuragic village. The surface was an ideal location for ancient anthropic activities, such as livestock, agriculture and/or deforesting. In general, the whole area was densely frequented during Nuragic times, as attested by other nearby important archaeological sites.

After <sup>230</sup>Th dating (n=20), the studied stalagmites comprehensively span the last ~7000 years. Peculiarly, they all show a net discontinuity: while the bottom appears brownish, the top is sensibly lighter in each of the 5 stalagmites. Such a marked change is also visible at micro scale, looking at the thin sections. Age modeling attested that this shift occurred, within uncertainties, toward the end of the “Nuragic” era, when Sardinia had first strict contacts with Phoenicians (a phase called “Orientalization”, ~700-600 BC), was then invaded by Punics (~500 BC) and later controlled by Romans (Depalmas & Melis, 2010). We here start to investigate the meaning of such a petrographical and geochemical discontinuity. Is it related to climate? Were different uses of the land above the cave, boosted by the arrival of new cultures, playing a role? Could climate and anthropic-cultural factors be interconnected? We will try to respond to these questions by comparing <sup>230</sup>Th dating, stable isotopes and petrography within the archaeological framework of the studied area.

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## **A speleothem-based reconstruction of the Late Quaternary climate-environmental-human nexus in the Kurdistan Region of Iraq**

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*Keywords:* speleothems, Ancient Mesopotamia, Paleoclimatic reconstruction, Holocene.

During the late Quaternary, the Kurdistan Region of Iraq (north-eastern part of ancient Mesopotamia) was the scenario of several fundamental cultural events including the dispersal of *Homo* to Eurasia, the origin of agriculture and adoption of domesticates, the beginning of urbanization, and the formation of the first state entities. The role played by climate and environmental changes on these cultural processes was highly debated, but local, continuous, and well-dated paleoclimatic records are still missing. In this contribution, we present the preliminary results of a palaeoclimatological and paleoenvironmental investigation in this area, which aims to reconstruct a detailed framework of the relationship between global climatic changes, regional environmental and hydrological responses, and human adaptation during the Late Quaternary, with a special look to the Holocene. Speleothems were collected along the eastern slopes of northern Zagros from the Hassārok Cave, near Shaqlawa township, in the northern Kurdistan Region of Iraq. Preliminary geochemical and geochronological results provide information on Holocene climatic variability in the region. Environmental and paleoclimatic data have been compared with archaeological information to infer and quantify the effects of climatic changes (if any) on human exploitation of natural resources, settlement dynamic and major shift in subsistence strategies and land use.

## **Deglacial and Holocene variations of the southern westerly wind belt and sea surface temperatures as recorded in Chilean margin sediments**

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*Keywords:* paleoclimatology, Holocene, circulation, Chile.

The westerlies are major zonal atmospheric circulation systems in both northern and southern hemispheres. The southern westerly wind belt (SWW) substantially contributes to the forcing of the deep and vigorous Antarctic Circumpolar Current (ACC). Wind-induced upwelling raises large amounts of deep water to the ocean's surface in this circumpolar belt affecting the global thermohaline circulation and atmospheric carbon dioxide contents. Therefore, the southern westerlies exert a strong control on global climate and oceanography.

The SE Pacific off southern Chile, where the SWW and ACC intersect with South America, represents an important area for understanding the behavior of southern hemisphere mid- and high-latitude climate. Chile is ideally located to reconstruct past variability of the SWW since the westerlies nearly entirely control precipitation on the western side of the Andes in southern South America, with an extreme north-south rainfall gradient. In present-day austral winters, the SWW extends northward providing rainfall to central Chile (33-40°S) and occasionally northern Chile (up to ~27°S) but zonal winds and rainfall are reduced in its core zone in southernmost Chile (50-55°S). During austral summer, the zonal wind pattern shows a latitudinally more confined and intensified SWW with maximum rainfall over southernmost Chile.

Paleo-precipitation estimates based on terrigenous sediment input changes off northern and central Chile agree with terrestrial records that glacial rainfall was higher in the semiarid part of Chile suggesting stronger glacial westerlies at the northern margin of the SWW. Less is known on glacial precipitation in the present core zone in southernmost Chile because this region was largely glaciated during that time. Holocene records suggest, however, a distinct latitudinal anti-phasing of precipitation/wind changes between the southern core zone of the SWW and the northern margin in central Chile. During the early Holocene, the core westerlies were enhanced and the northern margin was reduced, whereas the opposite pattern is observed in the late Holocene. These Holocene changes resemble modern seasonal SWW variations and can be best explained by varying sea-surface temperature (SST) fields in the Pacific. The analogy to modern seasonal changes implies that a latitudinal expansion of the SWW during cold phases ("winter-like") and contraction during warm climate conditions ("summer-like") may have been likewise important for the behavior of the SWW on glacial/interglacial time-scales and over the glacial millennial-scale fluctuations.

For the late Holocene, detailed temperature reconstructions are important for contextualizing modern climate change in the SE Pacific. Superimposed on the late Holocene cooling, we observe multicentennial-scale SST variability, including relatively cool SSTs corresponding to the Medieval Climate Anomaly, and warmer SSTs corresponding to the Little Ice Age.

## Perito Moreno glacier: a multidisciplinary study on its Late-glacial and Holocene dynamics

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**Keywords:** Perito Moreno, Southern Patagonian Icefield, high-resolution seismic survey, Lago Argentino, Holocene glacier fluctuations.

Perito Moreno glacier is one of the most studied glaciers in Patagonia, and probably the most well-known in the world. Currently, it has two calving fronts in Lago Argentino, one discharging within Brazo Rico/Brazo Sur to the east and the other within Canal de Los Témpanos to the north. Whereas most of the Lago Argentino outlet glaciers underwent considerable ice mass loss and retreated during the last 80–100 years, Perito Moreno glacier shows an apparent anomalous behavior and may be regarded as having been stable since 1920. Periodic advances of the Perito Moreno glacier's front form a natural ice dam as it progresses across the rocky shore of the Magallanes Península. That event blocks the water flow from the Brazo Rico–Brazo Sur arms of Lago Argentino, raising their water level. Spectacular water outburst have occurred semi-periodically when the ice-dam collapsed, as the most recent episode of March 12, 2018.

Between November 2017 and April 2019, OGS and CONICET-University of Buenos Aires performed three geophysical surveys in the lake arms hosting Perito Moreno glacier, i.e., Brazo Rico/Brazo Sur and Canal de Los Témpanos. These campaigns have been financed by the Italian Ministero degli Affari Esteri e della Cooperazione Internazionale (MAECI) and Ministerio de Ciencia y Tecnología (MinCyT) within a bi-lateral Italian-Argentinean scientific collaboration. High-resolution seismic profiles, complemented with bathymetric profiles, have allowed to map the whole lake floors of Brazo Rico/Brazo Sur and the southern part of Canal de Los Témpanos, and to identify the main seismostratigraphic units within the glacio-lacustrine cover (Lozano et al., 2020). In addition, several sediment cores have been recovered from a small inlet in the eastern sector of Brazo Sur. All these data represent an unprecedented geological and geophysical dataset which allowed us to: (i) propose an evolutionary scheme, albeit simplified, of the Late-glacial dynamics of the Perito Moreno, based on the sequence of moraines identified along the two arms of Lago Argentino (Lodolo et al., 2020a); (ii) constrain the latest major advance of Perito Moreno glacier, occurred at ca. 6000 kyrs BP (Lodolo et al., 2020b); (iii) provide evidence of a Little Ice Age ice-damming episode (324–266 cal yrs BP) as revealed by radiocarbon dating of a vegetal fragment found near the top of a recovered sediment core (Caffau et al., under review).

The outcomes of our studies represent a further step to decipher the complex glacial dynamics of southern Patagonia, and highlights the key role played by both subaqueous glacial bedforms as signatures of the glacier imprints within lake floors and by glaciolacustrine deposits as archives of information for decoding past climatic conditions at high latitudes.

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## The planktonic foraminifera *Globorotalia truncatulinoides* in Central - Western Mediterranean Sea during the Little Ice Age

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Keywords: *Globorotalia truncatulinoides*, Maunder minimum, Little Ice Age, Mediterranean Sea, Mixed layer.

The study of the climate changes of the last centuries allows comparison of data from historical documents, instrumental and paleodata records with multi-decadal variability arising from external forcing and internal climate variability. In this framework, the marine fossil records represent a fantastic archive to document the climatic variability over the last 500 yrs.

In this framework, *Globorotalia truncatulinoides* oscillations have been recorded from several marine sediment cores collected in the central and western Mediterranean Sea. *G. truncatulinoides* represents a deep dwelling winter species in the Mediterranean Sea and its life-cycle is characterized by a vertical migration in the water column. The abundances of this species over the last 500 yrs demonstrates its potential value as bio-indicator of particular oceanographic condition during the Maunder Minimum (MM) event of the Little Ice Age (LIA). The comparison between the *G. truncatulinoides* abundance patterns of the Balearic Basin, central and south Tyrrhenian Sea and central and eastern Sicily Channel allows to highlight a similar response of this species during the MM event in the central-western Mediterranean Sea.

The ecological meanings of this species and its peculiar high abundance percentage values in the total assemblages suggest the development of enhanced vertical mixing conditions during MM winter season with a strong advection of nutrients from the nutrient-rich deeper layers and enhances the productivity levels in the mixed layer. The intensified vertical mixing could be linked to persistence of an atmospheric blocking event recorded by several authors during the MM. In fact, this time-interval is characterized by an atmospheric blocking event. These particular climatic conditions could be responsible of intense deep vertical mixing phenomenon during the winter season producing the ideal ecological conditions for *G. truncatulinoides* proliferation. In addition, we suggest that maximum abundance of *G. truncatulinoides* left coiled is a response to more active dense water formation within the Mediterranean Sea during a cold time-period such as the MM.

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## **Palaeo-Science and History, a bridge between palaeoenvironmental research and history in Late Holocene**

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*Keywords:* palaeoenvironment, Late Holocene, History.

Palaeoenvironmental and historical researches are a long, consolidated traditions. Both of them are based on the integration of several disciplines. Moreover, the number of available studies is impressive, and they cover, even if with different extent, the entire globe. It is also noteworthy that palaeoenvironmental data are absolutely interconnected with human history, in particular in the Late Holocene. A careful analysis, however, highlights that palaeoenvironmental and historical study are usually superficially linked. Combined studies that include equally palaeoenvironmental and historical data are still rare, the current approach is to include the counterpart superficially. Palaeoenvironmental study usually look at the main historical events without take in consideration the available related written sources, for instance to economy and population in the region of interest. On the other side, historians look specifically at palaeo-data without a complete view of the possible implications. This approach brings to an oversimplification of the past phenomena and to the loose of potential knowledge hidden in the produced data. It is also true that the consilience suffers from some limitations, first of all challenge of merging different spatial and in temporal scales of produced data. Our knowledge is not yet at the stage to overcome this limitation but a lot can be done in order to bringing the two realities, unifying different research methodologies that addressing similar problems. The Palaeo-Science and History group of the Max Planck Institute explores the ways in which the environmental sciences converge with humanistic discipline that focus on the past. Both palaeo-scientists and historians are involved equally in the project with the common scope to achieve mutual understanding between - and learning from - the representatives of different humanistic and natural scientific disciplines within a single team. Some examples starting from the study of paleoenvironmental sites located in Italy and Greece will be here discussed in order to demonstrate the potentiality of the proposed approach. The important connection between climate change and human events, with a special focus on pandemics, will be taken in consideration allowing to draw a better reconstruction of the interaction between climate and society in history.

## A Late Holocene pollen record from marine sediments in SE Sicily

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*Keywords:* marine palynology, Holocene, Roman Humid Period, Little Ice Age.

The new pollen record from marine core SW104\_ND2-ND2, collected in the Sicily Channel 20 km from the coast, is presented. The central position of this marine record in the Mediterranean Basin is strategic to investigate past climate variability and ecological changes in a transitional climatic zone, highly sensitive to hydroclimatic variations. The intricate interplay of the climatic patterns acting over the Central Mediterranean, North Africa, and continental Europe determines a complex bioclimatic configuration, which is also reflected in the floristic richness and vegetational diversity of SE Sicily. Our analysis provides a detailed reconstruction of palaeoecological changes in relation to climatic variability and human impact over the last 3000 years.

The pollen record depicts a permanent open vegetational landscape with several fluctuations of land cover, corresponding to alternate forests expansions and reductions. This pattern is consistent with fluctuations in solar activity and the cyclicity of independent stratigraphic evidence at a global scale. The palynostratigraphy of the study record, based on changes in vegetation structure and floristic composition, reflects the main climatic events in historical times. During the Roman Period, a forest development is observed that suggests a centennial-scale humid climate, matching the so called Roman Humid Period. In contrast, a marked decrease in arboreal pollen percentages and concentration is observed since the 14<sup>th</sup> century AD, suggesting dry climatic conditions during the Little Ice Age. The comparison of our palaeovegetational reconstruction with independent palaeoclimate proxies reveals the recurrence of arid phases concomitant with negative or declining positive phases of the North Atlantic Oscillation (NAO), underlining the pivotal role of this forcing in determining precipitation distribution at centennial to decadal scales. At the same time, the detection of African taxa in the pollen record, testifying the southwestern provenance of air masses, suggests an interaction of northward shifts of North African high pressures with NAO-determined synoptic conditions. Extra-regional pollen inputs are especially frequent during the last millennium, indicating an increasing influence of the North African anticyclone over the Central Mediterranean region.

The SW104\_ND2-ND2 pollen record offers new detailed information on the extent of human impact on the landscape in relation to historical management policies and land use, and provides insights into past vegetation trends, atmospheric dynamics, and hydroclimatic conditions, which contribute to a better understanding of Late Holocene climate variability in the Central Mediterranean.

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## Water-Masses exchange through the Strait of Sicily during the Last Deglacial and Early Holocene

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**Keywords:** Western Sicily, Mediterranean Thermohaline Circulation, sapropel S1, Younger Dryas, Nd isotopes.

The Mediterranean is a semi-enclosed sea formed by two sub-basins, the eastern Mediterranean (E-Med) and the western Mediterranean (W-Med), connected through the Strait of Sicily. Four main deep-water convection cells fuel the Thermohaline circulation of the Mediterranean (Med-THC). In the E-Med, deep water is formed in the Adriatic Sea and the Aegean Sea, while an intermediate-water is formed in the Levantine Sea (Levantine Intermediate Water, LIW). The Western Mediterranean Deep Water is formed in the Gulf of Lions. Since all cells are interconnected, variations in one cell could be transferred to the others by modifying the Med-THC. The present study focuses on the analysis of the sediment core NDT-6-2016 at the west flank of Sicily channel, recovered at 1066 m of water depth, which is nowadays located below the interphase layer between the eastern and western originated water-masses. Therefore, this location is suitable for exploring changes in the inter-basin water exchange along the last 15 kyr cal. BP. Nd isotopes measured in planktic foraminifera coatings allow estimating changes in the export rates of the eastern Mediterranean source-water (ESW) masses underlying the occurrence of two anomalous events: The Younger Dryas characterized by an outflowing excess of ESW and the last sapropel (S1) with opposite circumstances. The export rates of EMS waters are estimated to have been up to three times higher during the YD than during the S1. These results are discussed in the context of other geochemical, sedimentological and micropaleontological proxies that allow us to have a more complete picture of the oceanographic changes associated to these events of Med-THC major reorganization.

**S22.**

**Quaternary climate and sea level change**

*CONVENERS AND CHAIRPERSONS*

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## Holocene RSL evolution in the Bay of Cádiz (SW Spain) from stratigraphic sea-level markers

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Keywords: Relative sea-level change, database, coastal environments, GIA models, Southern Spain.

The Bay of Cádiz, located in the South Atlantic Iberian margin, is constituted by low-lying coasts, mainly made of sandy barriers and salt marshes, that during the Holocene were affected by erosional and progradational episodes, with the development of subsequent beach ridge systems. The aim of this study is to reconstruct the Holocene coastal morphoevolution of the Bay of Cádiz in terms of relative sea-level (RSL) variations and related vertical displacements (VDs) considering different types of stratigraphic sea-level markers (SLMs) from new boreholes and bibliographic data (Dabrio et al., 2000; Arteaga et al., 2008; Alonso et al., 2015; Salomon et al., 2020; Caporizzo et al., 2021) located within the emerged sector of the study area. Along the stratigraphic successions, different depositional environments were detected. While salt marsh and intertidal deposits were interpreted as high precision sea-level index points (Vacchi et al., 2016), marine and fluvial deposits were considered as marine and terrestrial limiting points helping to establish upper and lower limits for the positioning of the Holocene RSLs. The collected RSLs were included in a comprehensive SLMs database, standardized according to the recent international guidelines for RSL studies (Khan et al., 2019).

Finally, the RSL data were further compared with new GIA curves modelled for the Gulf of Cádiz, enhancing an overall subsidence controlling the morphoevolution of the coastal plain during the Holocene.

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## New insights into the RSL evolution in the Ross Sea area, Antarctica

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*Keywords:* Antarctica, Holocene, sea-level change, AMS dating.

The definition of the Relative Sea Level (RSL) postglacial evolution of near field regions (e.g., those regions which were covered by the ice-sheets during the last glacial maximum, LGM) provides key information to infer parameters relating to changes in climate, regional ice-sheet variations, the rate and geographic source of meltwater influx.

In these regions, Relative Sea Level dropped by many hundreds of metres as a consequence of the isostatic ‘rebound’ of the solid Earth. Geophysical models can simulate the isostatic process. However, geological data obtained from coastal deposits is needed to both constrain the models and to test the accuracy of predictions made using them.

Here we produced a new set of sea-level data in Antarctica, Terra Nova Bay, by using different samples collected in the last decades during different Antarctic expeditions. In particular, AMS dating was performed on biological remains as guano, sealskin, shells found in raised beaches placed along the coasts of the Ross Sea, which has been occupied by the East Antarctic Ice Sheet (EAIS) during the LGM. The area is apt to unravel the Holocene deglaciation history (e.g., define the earliest moment of the ice retreat) and to better constrain glacio-hydro-isostatic adjustment (GIA) models due to presence of dated raised beaches and marine sediments on the ice-free land up to c. 30 m above sea-level (Baroni and Hall., 2004). The new data were flanked to the previously available data which were standardized according to the latest IGCP protocols (Khan et al., 2019). The new suite of RSL index, marine and terrestrial limiting points allowed to produce a new RSL record for the area which spans the mid to late Holocene period. Our dataset better documents both the timing and the magnitude of the continuous RSL drop which characterized this coastal region. These data are very important to quantify the GIA response in this key sector of the Antarctic continent.

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## New insights into the stratigraphic and tectonic evolution of the Policastro Gulf, southern Apennines, Italy

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**Keywords:** Policastro Gulf, land-sea correlation, wave-cut platforms, sea-level indicators.

A study based on the identification and characterization of Late Quaternary sea-level indicators, integrated with offshore seismic stratigraphic data has been carried out in the Policastro Gulf, south Italy, in order to reconstruct a comprehensive stratigraphic, tectonic framework and sea-level changes of the study area.

A morpho-stratigraphic study has been performed to shed light on the Late Quaternary vertical movements of the coastal region of the Policastro Gulf, where sea-level indicators, e.g., wave-cut platforms, the upper limit of *L. lithophaga* boreholes, and shallow-water deposits crop out up to 170 m above sea level (a.s.l.). The age of the highest marine terraces is still unknown, whereas new chronologic constraints are available for the shorelines standing up to a few tens of m a.s.l. (Cerrone et al., submitted). Recently dated marine terraces consist of wave-cut platforms carved into the Triassic to Miocene bedrock, which are covered by a few metres thick succession of biocalcarene bearing shore-face fauna. Age dating of biocalcarene deposits has been constrained by U-series measurements on *Cladocora caespitosa* corals and speleothems (Cerrone et al., submitted). Based on morphostratigraphic position of analysed marine terraces, the uplift, until at least, the latest stage of the Last Interglacial (MIS 5a) has been reconstructed. Fieldwork has evidenced the presence of fractures and faults, some of which with offset of a few metres, affecting the marine terraces.

An integration of outcrop data with offshore geophysical investigation is being carried out in order to compare the onshore evolution of the coastal sector with the offshore depositional system and structures.

The geophysical dataset includes a high-resolution marine DTM of the continental shelf and upper slope of the Policastro Gulf derived from multibeam bathymetry offshore, and ~ 160 km of high-resolution single channel (sparker 1KJ) profiles running parallel to the Gulf coastline.

Seismic stratigraphic interpretation of sparker profiles suggests the offshore evidence of a tectonic phase that predates the forced regressive deposits following MIS 5a, along with a distinct phase of sea level lowstand, accompanied by the occurrence of lowstand prograding wedges and marked by the development of a ubiquitous unconformity, likely associated with the Last Glacial Maximum (LGM).

The first results of land-sea correlation along the coastal zone of the Campania-Basilicata-Calabria boundary provide new constrains for the understanding of the Late Quaternary stratigraphic and tectonic evolution of the area, with specific reference to the vertical movements in the southern sector of the Policastro Gulf.

Cerrone C., Ascione A., Robustelli G., Tuccimei P., Soligo M., Balassone G. & Mormone A. (submitted) - Late Quaternary uplift and sea level fluctuations along the Tyrrhenian margin of Basilicata-northern Calabria (southern Italy): new constraints from raised paleoshorelines. Geomorphology.

## The Rock Surface luminescence Dating: a new technique to date Late Quaternary gravelly marine terraces

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*Keywords:* Eemian/Tyrrhenian stage, gravelly beaches, luminescence.

The Luminescence dating method is based on the capability of quartz and k-feldspar to absorb and store energy from environmental ionising radiation and release it after sunlight exposition. The method date the last daylight exposure of these siliciclastic grains. Sun exposition also for very little time bleached (zeroed) the system that, eventually, could be recharged again. Recently, Sohbaty et al. (2011) demonstrated that the zeroing effect of light on luminescence signal works also on rock surfaces, leaving an increasing residual signal with depth. On this principle is based a brand-new luminescence technique termed Rock Surface Dating (RSD), that analyses the luminescence signal-VS-depth profiles and can yield both burial and exposure ages of rock surfaces. The RSD is used to calculate the burial age of gravelly sediment (pebbles to boulders) and, it has been successfully applied on Holocene gravelly beaches deposits (Souza et al., 2021).

The Late Pleistocene marine terrace of Cala Mosca (Sardinia, Italy) is composed of gravel beach deposits and considered one of the Mediterranean Sea reference-sites for the Last Interglacial (Eemian/Tyrrhenian; Marine Isotopic Stage 5e). The sedimentary sequence is characterised by a thick cobbly transgressive gravel lag resting unconformable on the wave cut platform carved on Miocene bedrock overlain by a well-developed, highly fossiliferous, prograding mixed sandy-gravelly pocket beach system. The attribution to Tyrrhenian of the marine terrace, has been based on presence of fossils of the so-called “Senegalese fauna” (*Strombus bubonius* and *Patella ferruginea*) considered typical of the Eemian/Tyrrhenian stage and U/Th ages performed on fragments of *Cladocora caespitosa* ( $138 \pm 8$  ka and  $122 \pm 5$  ka) which confirmed the MIS 5e stage.

Here we present the preliminary independent results performed with RSD technique on cobbles collected at the base of the Cala Mosca gravelly beach deposits.

The RSD estimated burial age is of  $117 \pm 8$  ka. This is in good agreement with previous data, confirming the enormous potential of RSD method to date gravel beach deposits and extending its application to Late Quaternary period. Furthermore, the cobbles exposure-time before burial has been estimated of about two months, giving some clues on the beach dynamics.

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## Morphological quaternary evolution of coastal plain in response to sea-level changes: example from South-East Sicily

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*Keywords:* transgressive deposits, Hyblean plateau, multibeam, seismic stratigraphy.

Transgressive deposits accumulate during relative sea-level rises and accompanying the landward migration of the coastline can be recognised through gradual or abrupt landward shifts of facies, or deepening-upward facies trends that culminate in a surface of maximum flooding.

The offshore area of Marzamemi (SR, Sicily), in the south-eastern portion of the Hyblean foreland, represents an excellent site for the study of transgressive deposits and their connection with the sea-level changes. From a geomorphological point of view, the study area is part of the Pantani area, a coastal stretch characterized by a series of lagoons, elongated parallel to the actual coastline and separated by the open sea by elevated ridges of Tyrrhenian calcarenites and by coastal sand barriers. In this area, through the integrated interpretation of new multibeam data (MBES) and high-resolution seismic profiles (SPARKER), we have reconstructed the development of deposits connected to the Transgressive System Tract and Highstand System Tract of the last eustatic cycle.

Along the northern sector, three submerged lagoonal systems (L1, L2 and L3) mark important steps, of the Late Quaternary sea-level rise, possibly representing periods of lowered sea-level rise.

The deepest lagoon L1 is bounded to the west by the 45 m isobath, which identifies a cusate relief representing a paleo-coastline constituted by the outcropping Tyrrhenian substratum (Calcarenites of Marzamemi), only locally covered with highstand deposits. Southwards, the L1 is characterized by a smooth morphology interpreted to correspond with beach deposits, while in the central portion a system of tidal bars and channels is widespread as imaged in the seismic profiles. Westwards, the lagoon L2 marks a second step of the last sea-level rise, with the development of a paleo-coastline in correspondence of the 35 m isobath. The L2 shows morphological features similar to the L1, with the presence of extensive beach deposits to the south and two cliffs that bounded L2 to the west and to the east. Finally, 20 m isobath corresponds to the third significant step of the sea-level rise, and is associated with the paleo-coastline bounding to the west the lagoon L3. The latter hosted two islets and was confined to the east and west by high cliffs made up by the calcarenite substratum. Only to the south L3 displays a smooth morphology corresponding to beach deposits. Furthermore, a wide delta oriented west-east and characterized by an irregular trend due to the presence of numerous distributary channels is present within L3.

In the southern sector, likely due a different inheritance of regressive morphologies the transgressive setting features was significantly different and submerged lagoons did not form. Here the outcropping calcarenite substratum is affected by the development of meandering paleo-rivers and karst structures, such as numerous depressions (poljes), commonly developed along the Mediterranean karst regions.

## An expanded Holocene archive at the mouth of Mirna River (northern Istria, Croatia)

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Keywords: Northern Adriatic, sea-level changes, paleofloods.

The possibility to find significant information about the relative sea level during the Early Holocene is related to the rare settings where sedimentary sequences recorded that interval, as in the few deltaic plains or in enclosed basins (e.g. Brunović et al., 2019). For this motivation along the eastern side of the Adriatic the index points of past relative sea level are few and almost completely related to the upper Holocene. A favourable situation exists near the city of Novigrad (Croatia), at the mouth of the Mirna River, that has the largest fluvial catchment of Istria and experienced a deltaic progradation of about 12 km along the final tract of its karst valley (Felja et al., 2015).

We analysed the Holocene deposits recorded in core MIR1, that was drilled near the mouth of the Mirna River in the framework of a joined project between Padova and Zagreb universities. The borehole reached a depth of 120 m and documented that the thickness of Holocene sediments is about 34 m. The core was investigated for its sedimentology and stratigraphy, supported by several analytical methods which considered in detail the following properties: grain size, radiocarbon, C/N, molluscs, foraminifers, pollen, magnetic susceptibility.

The Holocene sequence documented in core MIR1 is an expanded record that allows a detailed investigation of the paleoenvironmental evolution. In particular, the quantitative analyses of pollen and foraminifers, coupled with nine radiocarbon dates, support the detection of the subtle variations of salinity and vegetation cover.

After the LGM, the sea reached the area about 10.4 ka cal BP and was afterwards characterized by a lagoon environment with a relative temporary pause in the rising trend between 9.7-9.3 ka cal BP, when the level was around -31 m Mean Sea Level (MSL). This setting was after modified by the rapid drowning of the valley that become an estuary. The maximum flooding occurred in the valley around 7 ka cal BP, when the coastal environment probably almost reached the area of Ponte Porton, 12 km inland. Deltaic progradation started in that period and the present position of the coast was reached only few centuries ago, when the reclamation activities started and were completed during the first part of the 20th century.

A vertical aggradation of over 10 m occurred in MIR1 between 5.5 and 4.0 ka cal BP, when the delta front was near the borehole site, creating a very expanded record of the alluvial history of the river. At a depth of 2.5 m salt marsh deposits of Roman age are recorded in the core and pollen analysis clearly documents the traces of human impact.

In core MIR1 an expanded and continuous sequence of the Last Interglacial is also documented, thus the Holocene interval represents an important analogue for inferring changes and similarities between the present and the Last interglacial conditions along the eastern side of the Adriatic.

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Felja I., Fontana A., Furlani S., Bajraktarević Z., Paradžik A., Topalović E., Rossato S., Čosović V. & Juračić M. (2015) - Environmental changes in the lower Mirna River valley (Istria, Croatia) during the Middle and Late Holocene. *Geologia Croatica*, 68(3), 209-224.

## **Core MIR1 (Istria Peninsula, Croatia): an expanded paleo-environmental archive for the Eemian and Last Interglacial**

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*Keywords:* Upper Pleistocene, palynology, sea-level changes, Northern Adriatic.

Northern Adriatic is marked by an asymmetric setting, with the western side displaying low-lying sandy beaches and the eastern one showing rocky coasts. This strong difference is also mirrored by the available sedimentary record for mid and late Pleistocene in the Northern Adriatic continental shelf, which is rather well investigated in the Po and Venetian-Friulian plains, whereas it is yet totally unknown along the coasts of Istria and Dalmatia.

A 120-m long core was drilled near Novigrad, in the coastal SW Istria Peninsula (Croatia), during a joined research project between Padova and Zagreb universities. This sedimentary sequence consists of Quaternary deposits filling the karst valley at the mouth of the Mirna River, documenting the alternance of alluvial, brackish and marine facies.

Due to the gentle bathymetric gradient of its continental shelf, Northern Adriatic could potentially allow the accurate reconstruction of transgression and regression cycles, even recording subtle marine fluctuations. Moreover, the mountain catchment of Mirna consists of flysch formation supplying a large quantity of sediments, that supported the construction of delta. For instance, during the Holocene the river prograded along its valley for over 12 km, reaching a thickness of over 30 m (Felja et al., 2015).

Core MIR1, in collaboration with CNR-IGAG and CNR-ISMAR, was studied for its sedimentological and stratigraphic features, coupled by the analyses of microbotanical proxies (pollen, spores, algae), micropaleontology, molluscs, radiocarbon datings and magnetic susceptibility.

Along the core, at least four marine transgression sequences are preserved. Data testify that most of the stratigraphy is related to the Holocene and the Last Interglacial, with the boundary between MIS 6 and MIS 5 at about 75 m depth. The Eemian biostratigraphic unit of terrestrial (pollen) proxies is represented by an expanded sequence spanning for over 20 m and consisting of brackish and marine deposits displaying a rather continuous sedimentation and an apparent absence of hiatus, providing a great potential for high resolution paleoenvironmental reconstructions.

Another major value of the record is the occurrence of a 34 m-thick Holocene expanded sequence, embedding the last 10 kyrs, where the direct link between sea level and ecosystems changes could be investigated in detail and compared to the Last Interglacial.

The MIR1 sequence represents an unicum, preserving a high-resolution record from the eastern side of the Adriatic Sea, covering most of both the Holocene and the Last Interglacial. Moreover, MIR1 is only 100 km east of core Venice (Massari et al., 2004) and from other Pleistocene archives documented in different cores such as AZX (Pini et al., 2009) and Fimon (Pini et al., 2010), allowing to depict of vegetation patterns and plant species distribution changes in time in the Adriatic area.

Felja I., Fontana A., Furlani S., Bajraktarević Z., Paradžik A., Topalović E., Rossato S., Čosović V. & Juračić M. (2015) - Environmental changes in the lower Mirna River valley (Istria, Croatia) during the Middle and Late Holocene. *Geologia Croatica*, 68 (3), 209-224.

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## **Biological and geomorphological indicators of mid-Holocene raised sea levels along the southern coast of the Arabian Peninsula (Sultanate of Oman)**

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*Keywords:* relative sea level, bioencrustation, notch, tectonic uplift, Holocene, Arabian Peninsula.

The Holocene relative sea-level evolution along the western portion of the Arabic Sea (Indian Ocean) is presently poorly constrained by geological data. Here, we present new insights into the relative sea level history of the Dhofar coast (southern Sultanate of Oman), placed at the southernmost tip of the Arabian Peninsula.

An assemblage of coastal notches and fossil bioencrustations were identified along the shore of the Wadi Darbat estuary, where previous works had identified raised beachrocks (Hoorn & Cremaschi, 2004), suggesting a relative sea-level higher than the present one during the Holocene. The 14C-AMS dating of bioencrustations allowed producing two relative sea level index points and one terrestrial limiting point.

Evidence provided by the index points testifies ca. 2 m relative sea-level higher than today during the mid-Holocene period (8 to 4 ka BP). This highstand is likely the result of the coupled influence of ocean syphoning and continental levering, which played a major role in far field sites since the end of the major deglaciation trends (Mitrovica & Milne, 2002). Our data are of particular interest because they represent the first evidence of a raised Holocene relative sea-level along the southeastern coasts of the Arabian Peninsula. These data are presently compared to the available glacio and hydro-isostatic models for this area. The comparison, will also allow to better quantify the moderated tectonic uplift recorded since the late Cenozoic (Hoffmann, 2020) which had also a significant role in controlling the coastal evolution in the last millennia.

Finally, our work provides some clues to refine the palaeoenvironmental evolution of the area, that bears relevant traces of human settlement since, at least, the Neolithic (Newton & Zarins, 2019) and particularly for the Wadi Darbat estuary, where human settlement is testified by the two important archaeological sites of HAS1 on the promontory of Inqitat and Sumhuran (from the Iron Age to the Classical Period, Lischi, 2019).

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## Transgressive lagoons and paleo tidal inlets in the northern Adriatic Shelf: geomorphological indicators of the last RSL rise

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Keywords: RSL rise, post-LGM, tidal inlets, Adriatic Sea.

The reconstruction of timing and modes of the last marine transgression is often hampered by the scarceness of available indicators due to bad preservation, lack of formation or difficult accessibility.

This is particularly true for the first period of the Holocene, between 11.7 and 7.5 ka cal BP, when the rate of transgression was high and the relative sea level rose from -80 to -10 m MSL (Vacchi et al., 2016).

Shoreline deposits and erosional landforms have long been recognized as the main geomorphological indicators of past sea levels. However, such features (e.g. beach ridges, tidal notches) can only form and be preserved over peculiar geometries of the shelf (Cattaneo & Steel, 2003).

A major group of potential indicators which, up to date, is largely underrepresented, is constituted by paleo tidal inlets. Being excavated up to several meters below the surrounding lagoon and filled during the migration or deactivation of the inlet, such landforms may represent outstanding archives with a potentially high chance of preservation from erosion. Paleo tidal inlets can be recognized and cataloged through shallow sub-bottom profiling methods.

Through the analysis of almost 7000 km of high resolution seismic profiles collected in the northern Adriatic Sea, more than 100 paleo tidal inlets were recognized. Such features date to the early Holocene and constitute one of the few widespread witnesses of the post-LGM marine transgression in the area.

The paleo tidal inlets of the northern Adriatic represent essential features for the paleo-geographic and paleo-environmental reconstruction and provide new data to constrain the position of transgressive coastlines. Reference examples of paleo tidal inlets have been recognized near the Po Delta (Ronchi et al., 2019), offshore of Chioggia (Ronchi et al., 2018), but also in the Gulf of Trieste.

The unexpected presence of widespread lagoons environments during a phase of strong RSL rise is the result of the interplay between sediment dispersal operated by the main fluvial actors of the area and phases of slowdown of the RSL rise.

This work recognizes the extensive distribution of paleo tidal inlets on a regional scale and sheds light on the phenomena affecting coastal plains in response to RSL rise, a topic of uttermost importance for the adaptation policies involving coastal areas.

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## When the Isonzo River flowed near Trieste, Koper and Piran: evolution of the fluvial systems in the Gulf of Trieste since the LGM

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Keywords: Isonzo river, Gulf of Trieste, LGM.

The Isonzo (Soča in Slovenian) is the easternmost large river of the southern Alps, with a catchment of 3400 km<sup>2</sup> extending between Slovenia and Italy. This fluvial system has been bounded to the east by the carbonate bedrock of the Karst and northern Istria, thus, it represents the limit of the large alluvial environments that characterize northern Italy, as the Po and Venetian-Friulian plains.

Through the analysis of a dense network of CHIRP profiles, multibeam DTMs and sediment cores collected in Adriatic seabed, both in the Italian and Slovenian sides of the Gulf of Trieste, this work reconstructs the evolution of the Isonzo River fluvial system at the scale of the entire gulf. Thanks to the recent geological map of Quaternary of Friuli Venezia Giulia Region (Fontana et al., 2019), it is also possible to relate the submerged areas to the present alluvial plain. Thus, the megafan of Isonzo can be considered on its whole extent.

In particular, among the different ancient channel belts recognized in this work, we reconstructed the planform and the stratigraphic architecture of paleo Isonzo over a length of almost 50 km, when this stream passed almost along the present coast, flowing near Trieste, Koper and Piran (cf. Trobec et al., 2017).

Alluvial systems are highly susceptible to environmental changes, such as variations in water and sediment discharge and in the position of the base level, making them natural data loggers capable of recording the various dynamics and forcing active at different scales over a certain time span. However, only extensive and detailed surveys allow to unwind the complex set of information stored in the alluvial stratigraphic record as documented in other alluvial systems of northern Italy (e.g. Fontana et al., 2014; Ronchi et al., 2021).

The fairly well-known boundary conditions in terms of structural, geological and recent climatic-related configuration of the Isonzo basin allow to understand the timing and style evolution of the Isonzo systems starting from the Last Glacial Maximum (LGM) up to the Early Holocene, when the area was flooded by the Adriatic.

Due to its position, along the late Quaternary the Trieste Gulf has been directly influenced by the water and sediment discharge supplied by the Alpine glaciers during the LGM and it after experienced the constrain of the post-LGM rising sea level. In describing the evolution of the Trieste Gulf, this work provides therefore a potential analogue for a wide variety of areas scattered over the world, from paraglacial environments to distal megafan areas and continental shelves with gentle slope, now submerged.

Our reconstruction also provides an ideal case study for the prediction of the impact of sea-level rise on natural systems, which is of paramount importance in the perspective of the ongoing global warming and the predicted loss of continental ice.

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## Evolution of the Neretva river delta (Croatia) and its importance for reconstructing the holocene relative sea-levels

Rossato S.\*<sup>1</sup>, Fontana A.<sup>1-2</sup>, Felja I.<sup>3</sup>, Juračić M.<sup>3</sup> & Mazzini I.<sup>4</sup>

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*Keywords:* delta plain, relative sea-level, fluvial trasgression, radiocarbon dating; paleontological analysis.

The Neretva River is a 225 km-long river that flows from the Dinaric Alps to the Adriatic Sea through Bosnia-Herzegovina and Croatia. It built up the largest delta plain of this sector of the eastern coast of the Adriatic Sea and prograded about 15 km during Holocene, mainly thanks to the siliciclastic rocks cropping out in the upper part of its catchment. The Holocene deposits of the Neretva River delta plain were investigated to identify and evaluate high-quality index points for reconstructing past Relative Sea Level (RSL).

Two manual cores (NER5, NER6) were realized in the wetlands near Opuzen, along the flank of a limestone hill, spacing 5 m. The cores reached the Mesozoic bedrock at a depth of 4.9 (NER5) and 8.2 (NER6) m. The recovered material was collected, and sedimentological, chronological, and paleontological analyses were performed in the laboratory.

The base of the deposits found on top of the limestone bedrock was radiocarbon dated to 3.2 ka cal BP, way after the submersion of the area by the sea. Above that interval, estuarine sediments accumulated up to about 3 m from the surface, where freshwater swamp/lacustrine environment started to occur in the area. Its origin, dating back to the 1st century AD, is related to the blockage of the outflow of the tributary valleys by the progradation of the Neretva River delta over the threshold of Opuzen. Since that moment, the situation remained almost stable until modern times.

The paleontological investigations focused on foraminifera, ostracoda, and mollusc associations, mainly consisting of benthic foraminifera and ostracods. These organisms are widely applied in the analysis of Holocene sea-level changes and in paleoenvironmental reconstructions of estuarine systems. The vertical markers of the RSL have been described with a standardized methodology, following the recent IGCP protocol developed for creating a database of past sea-level index points (e.g., Vacchi et al., 2016).

The combined use of sedimentological and paleontological analyses of two sediment cores and <sup>14</sup>C dating allowed recognizing different depositional environments and their succession in the marginal part of the Neretva delta plain during Holocene highstand. These data allow reconstructing relative sea-levels and give some constraining features for documenting the evolution of the Neretva delta area in the last 3000 years.

Vacchi M., Marriner N., Morhange, C., Spada G., Fontana A. & Rovere A. (2016) - Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: Sea-level variability and improvements in the definition of the isostatic signal. *Earth-Science Reviews*, 155, 172-197.

## **Last Interglacial sea-level proxies in the Western Mediterranean: a contribution to the World Atlas of Last Interglacial Shorelines database**

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*Keywords:* WALIS, sea level changes, MIS 5.

WALIS (the World Atlas of Last Interglacial Shorelines) is a global standardized database of MIS 5 sea-level proxies, which is being compiled by several authors thanks to the database structure and interface prepared in the framework of the European Research Council Starting Grant “WARMCOASTS”. Here, we present the results of an effort to review and standardize into the WALIS format the information reported in 179 published studies on Quaternary sea level index points in the Western Mediterranean. Our database contains 371 sea-level datapoints (sea-level index points and marine or terrestrial limiting points) and 304 associated dated samples. The database is available as Cerrone et al, 2021b (<https://doi.org/10.5281/zenodo.4497365>).

## **The Late Quaternary composite marine terrace of Cala Mosca site, SW Sardinia (Italy): global sea-level change VS Tectonic activity**

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*Keywords:* luminescence dating, pIRIR225, stratigraphy, facies analysis, Pleistocene, Mediterranean Sea, beach deposits.

The marine sedimentary sequence of Cala Mosca bay (Sw Sardinia) is well-known and studied since the beginning of the past century and is considered a key stratigraphic section for the Marine Isotope Stage (MIS) 5e (~125 ka) or “Tyrrhenian/Eemian” highstand around the Mediterranean basin. In particular, this sedimentary wedge is interpreted as a beach system placed on a wave-cut platform forming a single marine terrace craved on the Miocene bedrock.

A newly performed multidisciplinary (sedimentological, stratigraphical, chronological and tectonical) approach clearly reveals that the Cala Mosca single geomorphological marine terrace is in fact the result of two superimposed marine units (unconformity bounded unit U3a and U3b) separated by a composite unconformity surface associated with two different transgressive-regressive (T-R) cycles (T1 and T2).

The lower T1 cycle is characterized by a cobbly transgressive gravel lag resting unconformable (wave-cut platform) on Miocene bedrock overlain by a well-developed prograding mixed sandy-gravelly pocket beach system (regressive phase). Obtained luminescence ages (pIRIR225 protocol), date T1 at 137±7, 134±7 ka confirming the MIS 5e stage attribution.

The second marine cycle T2 lays unconformable on T1 and consists of a m-thick maximum gravelly body interpreted as a poorly-developed beach system formed on a rocky shore at the toe of retreating cliffs (transgressive phase). Obtained luminescence age dates T2 at 92 ± 6 ka supporting the MIS 5c stage attribution.

T1 and T2 two cycles are separated by a composite unconformity surface developed during the post-MIS 5e sea-level fall and subsequent rise (early MIS5c). The T1 deposits were almost completely eroded during the second transgressive event and T2 sedimentary bodies reoccupied in part the same position of T1 forming an apparent single morphological unit.

In this new light, the paradigm of Late Pleistocene tectonic stability of the Island seems to be abandoned and a more complex evolutionary history of Sardinia has to be build up. In particular, the interplays between global sea-level changes, region low-rate uplift, and localized rapid normal fault activity would explain the presence of a MIS5e and MIS5c composite marine terrace at the “locus typicus” of the Eemian in Sardinia.

## On the variability of the postglacial sea-level changes along the western African coasts

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*Keywords:* sea-level change, Atlantic coast, West Africa, Holocene, Last Glacial Maximum

A new database made of 430 radiocarbon dated sea-level data, allowed evaluating the variability of Relative Sea Level along the Atlantic African coast (Morocco to South Africa) since the Last Glacial Maximum (LGM). Sea-level data were standardized following the International Geoscience Programme (IGCP) protocols to produce a suite of validated sea-level index and limiting points. The Atlantic African coast database was grouped in 21 regions according to geographical position and the distance from LGM ice-sheets. A Gaussian model was then applied to the new suite of sea-level data to estimate regional rates of RSL change.

Our analysis indicates the RSL lowstand at the end of LGM did not exceed  $-105 \pm 4$  m as indicated by a suite of marine limiting points. This agrees with the recently produced global sea level curve (Gowan et al., 2021). Since the LGM, RSL rose rapidly with average rates of up to 15 mm a<sup>-1</sup> between 16 and 9 ka. The rates of RSL rise decrease to  $< 3$  mm a<sup>-1</sup> after  $\sim 7$  ka BP. The mid-Holocene illustrates the emergence of a RSL high-stand which exceed the present mean sea-level. This high-stand, produced by the combined effect of ocean syphoning and continental levering (Milne and Mitrovica, 2002) shows temporal and spatial variability along the western African coast. In those regions placed in the northern tropical region, the high-stand reached elevations up to 2.0 m between 6.5 and 5.0 ka BP and was followed by a gradual drop to the present datum. In the equatorial and southern tropical regions, we observed a delayed high-stand which occurred at about 4.0 ka BP followed by late Holocene fluctuations, which are not reproduced by current GIA models (Peltier et al., 2015). The origin of these fluctuations are presently difficult to explain but they can be related to an isostatic response to the Antarctic ice-sheet deglaciation. This new dataset allows providing new insights into the pre-industrial factors which controlled the sea-level evolution along the densely populated western African coast. These data are fundamental to provide constraints for more robust future sea-level projections of the west African coast in the framework of the on-going climatic change (Nicholls and Cazenave, 2010).

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## Implementing a cartographic repository of the postglacial Antarctic paleo-shorelines

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*Keywords:* Antarctica, cartography, geomorphological mapping, GIS, paleo-shoreline.

An improved understanding of the chronology of Antarctic ice sheet deglaciation since the Last Glacial Maximum-LGM represents a fundamental tool to better define the origin of past and future meltwater influx in the global oceans (Whitehouse et al., 2012).

Relict shorelines and other evidence of past Relative Sea Level (RSL) evolution were widely used to understand past ice sheet history and to improve predictions of climate-sea level relationship evolution (Khan et al., 2015). In the last decades, RSL data in the Antarctic region have been mostly produced using raised marine features such as beach and marine deposits, marine terraces and isolation basins. The chronology of these paleo sea-level stands has been established through geomorphological and stratigraphic techniques (John & Sugden, 1971; Fretwell et al., 2010) and supported by radiometric dating from samples found in beach deposits and marine/freshwater sediments (Simms et al., 2011; Watcham et al., 2011).

Here we present a new cartographic approach, currently carried out along the Antarctic Peninsula and South Shetland Islands, which has a twofold aim: (i) the creation of an open access dataset including information about paleo-shorelines by using a uniform collecting pattern, and (ii) the production of a coherent database which can be used for improved spatial analyses useful to define the Antarctic shoreline evolution as well as better constrain the chronology of the deglacial history. As demonstrated by other free data-repositories (<https://www.bgs.ac.uk/geological-data/national-geological-repository/>) and similar examples (<https://warmcoasts.eu/world-atlas.html>), the new cartographic instrument, built in web-GIS format, will represent a very important tool for Antarctic coast investigations and a tool for better focusing future researches.

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**S23.**

**The cosmic challenge: from interplanetary dust to the bricks  
of life**

*CONVENERS AND CHAIRPERSONS*

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## Characterization of Cavezzo, the anomalous L5 chondrite recovered by PRISMA

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*Keywords:* meteoroids, meteors and meteorites, Cavezzo.

The Cavezzo meteorite, felt on January 1<sup>st</sup> 2020, is the first meteorite recovered by the Italian PRISMA fireball network. Two specimens, weighing 3.1 g (F1) and 52.2 g (F2), were collected three days after the bolide was observed.

The two specimens have a completely different lithology, geochemistry, and oxygen isotopic composition. Specimen F1 is anomalous both for the textural-structural features, varying from chondritic to achondritic, and a very unusual modal mineralogy. Conversely, F2 characterization is closer to the one of an ordinary L chondrite, given its texture, crystal chemistry and modal mineralogy. The oxygen isotope composition of F1 plots at the boundary between the H and L groups, whereas F2 plots at the boundary of the L and LL fields. These results support the classification of Cavezzo as a L5 anomalous chondrite.

Measurements of F2 gamma activity revealed the presence of many cosmogenic isotopes (<sup>47</sup>Ca, <sup>52</sup>Mn, <sup>48</sup>V, <sup>51</sup>Cr, <sup>7</sup>Be, <sup>58</sup>Co, <sup>56</sup>Co, <sup>46</sup>Sc, <sup>57</sup>Co, <sup>54</sup>Mn, <sup>22</sup>Na, <sup>60</sup>Co, <sup>44</sup>Ti, <sup>26</sup>Al) with half-lives down to few days, thus confirming the recent fall of the sample. Short-lived cosmogenic radioisotopes are not often measured, since this is possible only for meteorites recovered just after the fall. Besides information about solar activity on different time scales, the measured concentrations of cosmogenic isotopes will provide constraints on the pre-atmospheric size of the meteoroid and shielding depth of the counted sample, to be compared with results from dynamical mass computed from PRISMA observations.

## VNIR bidirectional reflectance spectroscopy of natural impact glasses

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*Keywords:* Shock impact glasses, Reflectance VNIR spectroscopy, planetology.

Shock impacts frequently shape the crust of the Earth and (to a much greater extent) extra-terrestrial bodies. When objects with a big mass are involved, the collision may even lead to the formation of a new planetary body. One of the most common consequence of these processes is the transformation of the impacted rocks and soils into glass due to the shock wave. Using bidirectional reflectance spectroscopy in the VisNIR region (0.35 – 2.5  $\mu\text{m}$ ) we analyzed a suite of ten natural Earth glasses formed as a result of an impact with extra-terrestrial bodies. The material come from different places on the Earth and have heterogeneous chemistry. We sieved the powdered materials and a total of 8 equally spaced grain sizes between 0 and 250  $\mu\text{m}$  were produced and measured. We quantified the spectral features (band center, band centroid, band depth, spectral slopes etc.) of the shocked materials in order to gain as much information as possible about the composition and characteristics of the impacted materials. The dominant feature of the spectra is given by the absorption bands of Fe around 0.9-1 $\mu\text{m}$ , which sometimes forms a broad band extending to 2-2.3  $\mu\text{m}$ . In Fe poor samples is it possible to observe a small feature at about 0.6  $\mu\text{m}$  likely caused by absorption of Ti ions. Smaller features at about 1.4, 1.9, 2.2-2.3, are indicative of a mild alteration and/or water incorporation in the samples. Our results on shocked materials will be helpful in refining the spectral interpretation and constraining the role of glassy materials on remotely acquired data of planetary bodies.

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## VNIR spectral properties of olivine bearing Ungrouped Achondrites

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*Keywords:* meteorites, olivine, reflectance, asteroids, achondrites.

Reflectance spectra properties are one of the most important information we can acquire from different bodies in the Solar System to classify them. A natural sampling of extraterrestrial material is represented by meteorites that can provide crucial information on the origin and evolution of their parent bodies. At present, sample return missions are one of the primary goals of the Solar System exploration (e.g. Hayabusa 1 and 2; OSIRIS-REx). In particular, these missions are addressing asteroids formed by chondritic material, however among the minor bodies some have experienced process of differentiation and magmatic evolution and for these bodies the only sampling is provided by achondritic meteorites. These can span from primitive to highly differentiated and they are mainly composed of mafic minerals, feldspars and other minor compounds. These mineral phases can be investigated by VNIR spectroscopy to associate them to their parental bodies. In particular, within mafic minerals olivine is considered a paradox, as being a mineral forming the mantle of differentiated bodies, it would be expected to be present in a larger number of asteroids than it has been observed.

Here we present preliminary spectroscopic results of a set of ungrouped achondrites (e.g. Al Huwaysah 010, NWA 5400, NWA 6704, NWA 6112, A 881548) with different amounts of olivine and variable Fe-Mg composition. These samples are studied by means of the VNIR reflectance spectroscopy to compare their spectra with available ones from literature. This procedure allowed us to study the olivine composition in this spectral range and also the olivine amounts with respect the other main phases. From these samples we evidence how the olivine is clearly present in NWA 5400, Al Hawaysah 010, and NWA 6116. These meteorites are also the darker samples, with the first two samples showing a weak 2 mm band, indicative of the presence of pyroxene. The NWA 6704 and A 88548 are brighter and spectrally dominated by pyroxene, even if an asymmetry in the 1 mm band is present, suggesting the presence of olivine in lower abundance. These results are supported by detailed petrographic and mineralogical analysis of the selected samples. These achondrites are investigated both as powders and slab of rocks to show also the different effects due to the presence of a powdered regolith or a bedrock exposure. VNIR reflectance spectroscopy results will be also compared against possible parental bodies.

Moreover, we characterized also the MidIR (i.e. 7-14 mm) range, where vibrational absorptions associated to the silicates are present. These analyses allowed us to detect mineralogical variation for these materials and they could be used as a tool for future planetary exploration of small bodies and planetary surfaces.

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## Preliminary results on mineralogical and geochemical analysis on ungrouped achondrites

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*Keywords:* cosmochemistry, ungrouped achondrites, mineral chemistry, Cr isotopes.

Meteorites together with return mission samples represent the unique tools to investigate Solar System bodies. Among meteorites, ungrouped achondrites represent natural sampling of some primitive parent bodies and provide fundamental information about their genesis, the processes associated with the origin of our Solar System and the evolution of most evolved compositions.

These materials are usually investigated by indirect analyses that allow the characterisation of a large number of samples, but they usually are not able to achieve the high-precision level provided by direct analytical methods.

We present the preliminary results of a multi-technical approach combining mineralogical, petrographic, geochemical and isotopic characterisation of achondrite meteorites to provide a detailed characterisation of the samples. We selected a set of ungrouped achondrites with variable amount of olivine and other mineralogical phases (e.g., pyroxene, graphite, spinel). Three samples (NWA 2968, NWA 5400-paired 5363 and NWA 6704) were investigated through Scanning Electron Microscope and Electron Microprobe (EMPA) to determine the mineral chemistry of major (olivine, pyroxene and plagioclase) and minor phases (Fe-Ni alloys, oxides, sulphides, phosphates). Noticeable is the occurrence of previously unmentioned tenth-micron size inclusions with a garnet-like composition in NWA 2968 (a dunite with HED affinity), the nature of which will be further investigated by EBSD. Moreover, the presence of secondary phosphates in NWA5363 (Cl-apatite replaced by Fe-phosphates) points to Fe-rich fluid circulation on its parent body. Along with these classical analytical methods we particularly aim to combine these analyses with trace element abundance (by ICP-MS) and isotopic composition (by TIMS) to be performed both on bulk samples and, as a future application, to specific mineralogical phases. In this light, we aim to develop high-precision measurement protocols for Cr contents and isotope compositions (i.e.,  $^{53}\text{Cr}/^{52}\text{Cr}$  and  $^{54}\text{Cr}/^{52}\text{Cr}$ ). These will be further coupled with other methods (e.g., reflectance spectroscopy, oxygen isotopes) to reinforce the confidence of association of the studied samples with their parent body family. The preliminary experiments performed are carried out on a well characterised material, the international standard Allende, to test the validity of the preparation procedures (i.e., dissolution of silicates and other refractory phases, chromatographic separation) and the trace element content determination on meteoritic matrix, set up in the laboratories of the Earth Science Department of the University of Florence. The reproducibility of the isotopic measurements will be tested on the isotopic standard NIST979 and on other well characterised meteorite samples to be used as reference values.

## The geological history of a Martian volcano

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Keywords: Mars, meteorites, electron backscatter diffraction, atom probe tomography.

The nakhlite meteorites are igneous rocks from Mars (Treiman 2005). The nakhlites sample a single volcanic edifice that erupted several times between 1.4-1.3 Ga (Cohen et al., 2017). They have also been affected by hydrothermal activity on Mars ~630 Ma (Borg & Drake 2005) and were ejected from Mars in a single impact event at ~11 Ma (Treiman 2005). Therefore, the nakhlite meteorites are a key sample suite for understanding volcanic activity, habitability and impact processes on Mars.

A key challenge in making inferences regarding the red planet from the study of Martian meteorites is that the samples that we have on Earth lack their geological context – we do not know from where on the Martian surface they originated. Advanced machine learning crater counting algorithms are being developed to identify candidate craters (Benedix et al., 2020) while the Mars Sample Return campaign has been initiated to bring samples to Earth from known localities on Mars. Additionally, by applying new quantitative petrographic techniques it is possible to reconstruct the formation and geological history of the meteorites we already have such as the Martian nakhlite igneous rocks.

Here we applied correlative microscopy including electron backscatter diffraction, transmission electron microscopy and atom probe tomography alongside numerical simulations to Martian nakhlite meteorites to provide new insights into their geological history, including: 1) evidence of multiple igneous emplacement mechanisms (Daly et al., 2019a); 2) providing tight constraints on the geomorphology of the launch site on Mars (Daly et al., 2019b); 3) outline a analytical pipeline to maximize the science obtained by Mars Sample Return (Daly et al., 2020).

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## **Tell me who you are. The study of doubtful meteorites in meteoritics and its history. A case study**

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*Keywords:* Marsala, meteorite, pseudometeorite, meteorite collecting.

This presentation set out with the aim of assessing the role of doubtful meteorites in the history of meteoritics. With respect to the research question, the presentation investigated the presumed witnessed fall that was recorded in Marsala (Sicily, Italy) on the night between 15 and 16 December 1834. Very little was found in the literature on this “extraordinary phenomenon,” and previous studies (e.g., Boguslawski, 1854; Grady, 2000) observed inconsistent results on whether the event was meteoritic in origin, because no meteorite fragments had ever been recovered. This explains why the Nomenclature Committee of the Meteoritical Society have classified this event as a doubtful meteorite, i.e., an object for which there was significant uncertainty over whether it was a real meteorite or, in some cases, whether it ever existed. The goal of this presentation is to contribute to the knowledge of the role of the doubtful meteorites in the history of meteoritics and to characterize the event that occurred in 1834 in Marsala.

Thanks to the analysis of untapped sources, this presentation found that the event provoked a lively debate in the press and among the scholars of the time. Various Italian and foreign newspapers reported the news, while the pages of several Sicilian gazettes followed the scientific discussion about the real nature of the event.

Even if doubtful meteorites have been discarded because they were not followed by the recovery of any meteorite samples and, in some cases, there is no certainty whether they really occurred, this research has found that their investigation may reveal unknown historical and scientific data. Although the current study is based on the analysis of a single doubtful meteorite, the findings revealed interesting aspects relative to the early stages of meteorite research, to the dissemination of science news, and to meteorite collecting over the centuries.

Based on the results presented here, this presentation highlighted the role of doubtful meteorites as an important resource for the history of meteoritics and meteorite collecting as well as for studying the processes that have led to the scientific study of meteorites.

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## **PRISMA: an italian network to recover freshly fallen meteorites**

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*Keywords:* meteoroids, meteors, meteorites, fireball networks.

PRISMA is the italian fireball network dedicated to the observation of bright meteors. Its main purpose is to precisely confine the area of potential meteorite falls (strewn-field) and determine the orbit of progenitor bodies. PRISMA is active since 2016, building a collaboration involving more than 60 institutes, both public and private, among university departments, research centres, amateur associations, schools. Being coordinated by INAF, the Italian National Institute for Astrophysics, it is a member of the european network FRIPON. To date, PRISMA counts more than 60 all-sky detectors and has observed more than 2000 bright meteors. Four among them were meteorite-dropping bolides for which we computed a reliable strewn-field. In particular, on 4/01/2020 two meteorite pieces were recovered near Cavezzo (MO) in the area predicted thanks to the observations of PRISMA. This is the first recovery of this type in Italy and one out of 35 in the world up to now. More recently, in march 2021, a similar event was observed in the skies of southern Italy, near Isernia. Searches for the meteorite are still ongoing, involving the local people and volunteers.



## Two different parent bodies for mesosiderites and HED: planetesimals evolution in the Vesta source region

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*Keywords:* mesosiderites, Vesta, HED, oxygen isotopes, petrography, cosmochemistry, mesosiderites matrix, planetesimals, redox variations, iron-manganese ratio, iron magnesium ratio.

Mesosiderites are an enigmatic group of differentiated meteorites consisting of a mixture in roughly equal parts of metal and silicates, testifying to the mixing of crustal and core material without the involvement of mantle material. Because of the contrasting geochemical, isotopic, and spectroscopic evidence, the formation history of mesosiderites and their parental relationship with the howardite-eucrite-diogenite (HED) meteorite group (i.e., common provenience from asteroid 4 Vesta) is yet poorly understood and largely debated. In this contribution, we tackle the nature of this relationship in light of new high precision oxygen isotopes analyses of mesosiderites matrix, and of petro-chemical data of mesosiderites Um Hadid, Estherville, and Mt. Padbury. The oxygen isotopes analyses gave values for mesosiderites matrix of  $\delta^{17}\text{O}\text{‰}$   $1.660 \pm 0.159$  ( $2\sigma$ ),  $\delta^{18}\text{O}\text{‰}$   $3.620 \pm 0.318$  ( $2\sigma$ ) and  $\Delta^{17}\text{O}\text{‰}$   $-0.237 \pm 0.024$  ( $2\sigma$ ), which are compatible with the values of mesosiderites igneous clasts and of HEDs (Greenwood et al., 2006, 2015) and confirm their provenience from the Vesta source region. The concordant oxygen isotopes values of mesosiderites matrix and igneous clasts indicate that they are cogenetic. From the geochemical and petrological data, we identify the active processes in the mesosiderites parent body (MPB), before and after the addition of the metal portion. In particular, the variations of both molar Fe/Mn and Fe/Mg ratios in bulk rocks and pyroxenes of igneous clasts are indicative of active redox processes during their crystallisation in the MPB, before the silicate-metal mixing event. Analogue redox trends are not observed in HEDs and, moreover, the Mn vs. Fe<sup>2+</sup> (afu) trends of pyroxenes in mesosiderites and HEDs are indicative of different formation distances from the Sun. The similar  $\Delta^{17}\text{O}$  values of mesosiderites and HEDs imply that they formed in the same oxygen isotope reservoir, but geochemical and petrological evidence indicate that they underwent different differentiation processes. To conciliate this contradictory evidence we propose a two-parent body model, in which the MPB accreted in the 4 Vesta source region, underwent a complex differentiation (characterized by redox processes), then was hit by a molten metallic runner. Finally, the MPB broke up or was expelled from the main asteroid belt, making mesosiderites “orphan” meteorites and 4 Vesta not their parent body, but their aunt.

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## Physical properties of the 67P/Churyumov-Gerasimenko's dust revealed by the combined Rosetta's GIADA-MIDAS data analysis

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*Keywords:* comets, dust, surface morphology.

The ESA/Rosetta mission orbited the 67P/Churyumov-Gerasimenko comet for two years, escorting it through perihelion, occurred on 13th August 2015. The 67P's dust ejection has been detected in different stages of the comet's orbit by both remote observations and in-situ measurements.

This work merges data from the GIADA (Grain Impact Analyser and Dust Accumulator) (Della Corte et al., 2014) dust detector and the MIDAS (Micro-Imaging Dust Analysis System) (Bentley et al., 2016) atomic force microscope. The two instruments detected dust different in size (mm-sized vs mm-sized) and complementary dust properties (porosity and mass vs physical properties and 3D structure). GIADA measured speed of individual dust particles, that has been used to trace back their motion down to the nucleus surface, allowing the association of dust and surface properties (Longobardo et al., 2020). MIDAS collected micron-sized dust particles on several targets, each working in a defined period. Cometary dust was detected on four MIDAS targets: Target 10, Target 12 and Target 14 collected dust in three periods before perihelion, whereas the dust collected on Target 13 was released in an outburst occurred after perihelion.

Our first step was to compare the millimetric and micrometric dust flux measured by GIADA and MIDAS, respectively. We obtain a quite constant flux ratio, suggesting that MIDAS detected a fraction of the GIADA flux. In particular, because models suggest that no micron-sized particles can be ejected during the considered periods (Fulle et al., 2020), MIDAS detected fragments of the mm-sized dust particles detected by GIADA.

By applying the traceback procedure (Longobardo et al., 2020), we found that particles detected by the different MIDAS target are originated from morphologically different terrains. Analysis of MIDAS data suggests that the shape distribution on the four target is very similar. This imply that physical properties of compact particles are similar everywhere on the comet surface.

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## Evolution of Mercury-like lavas through aubrite meteorites: looking for sample analogs for the ESA/JAXA BepiColombo mission

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*Keywords:* mercury, aubrites, petrology, geochemistry, bepicolombo.

The NASA's MESSENGER mission reported that Mercury surface is mainly composed of basaltic lavas, with small areas composed of residual floating carbon phases due to a primordial magma ocean. In particular, compositional data obtained by X- and Gamma-ray spectrometers highlighted that basaltic lavas have unique characteristics among the differentiated planetary bodies (e.g., Solomon et al., 2018). Mercurian rocks appears to be extremely reduced, with very low Fe contents (< 2 wt.% Fe; with Fe/Si of ~0.06), an enrichment in Na and K, a wide variability of Mg and Ca, and a significant abundance of S (1.5-4 wt.%; e.g., Rothery et al., 2020). The composition of Mercury surface is so unique that we still do not have any terrestrial or extraterrestrial analogue. Only a few enstatite achondrites meteorites, the aubrites, have features that could, in part, resemble that of the Mercurian surface.

Aubrites are primarily composed of large crystals of the Fe-poor, Mg-rich orthopyroxene (enstatite; En ~99). They also have minor phases of olivine, Ni-Fe-Si metal, and troilite, which indicate a magmatic formation under extremely reducing conditions.

Recent works on MESSENGER-MDIS multispectral data suggested the presence of a few transitional elements such as Cr, Ti, Ni, and Co substituting Mg and/or Fe in pyroxenes (Lucchetti et al., 2018). Thus, to understand how the pyroxenes acquired such chemical abundances, and which magmatological meaning they have in the Mercurian magmatic system, we are acquiring Cr, Ti, Ni, and Co diffusion profiles in pyroxene in multiple aubrites (Pena Blanca Spring, Norton County, NWA 4537, NWA 6675). We are also planning to experimentally produce analog samples. Geochemical analyses will be performed using an EMPA system at the University of Milan and a LA-ICP-MS at the University of Pavia/CNR. This will allow us to: 1) better comprehend the formation and evolution of the Mercury crust; 2) derive spectral information from sample analogs in the range investigated by the SIMBIO-SYS/VIHI spectrometer on board the BepiColombo mission before it reaches Mercury.

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## Minerochemical and textural data of Northwest Africa 12722, a new carbonaceous chondrite from Sahara

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**Keywords:** Carbonaceous chondrites, classification, Saharan meteorites, NWA 12722.

Here are presented the minerochemical and textural features of a new carbonaceous chondrites from Sahara classified in 2019 at the Museo di Storia Naturale-SMA dell'Università di Firenze, Italy. A single piece weighing 68 g with traces of fusion crust was collected by nomads in Western Sahara and purchased by Hichame Mimaghador at Erfoud in 2018 from a moroccan dealer. CAIs are visible on the hand specimen cut surface. A total of 16 g specimen (inventory N° I3373) is on deposit at Museo di Storia Naturale dell'Università di Firenze-SMA. Mimaghador holds the main mass. This meteorite has been submitted for classification by the Nomenclature Committee of the Meteoritical Society under the name Northwest Africa 12722 [1].

Instruments and methods: BSE images and EMPA-WDS analyses were undertaken at the Firenze IGG – CNR laboratories with a Jeol microprobe Oxygen isotope analysis was undertaken at the Open University.

Textural features: the thin section displays a chondritic texture, with scattered PO and POP chondrules set in an abundant fine grained matrix (60 vol% from point counting, n=520). Chondrules are often metal rimmed and range from 600-800 µm in dimensions. POP chondrules display unequilibrated fayalitic olivine and Mg-rich orthopyroxene crystals with minor diopsidic pyroxene; matrix is fine grained and almost entirely composed by fayalitic olivine mixed with Ca-rich pyroxene and albitic mesostasis; opaque phases are mainly represented by iron oxides rimming chondrules and magnetite grains inside chondrules; the weathering grade is moderate while the shock stage is medium.

Minerochemical features: SEM and EMPA analyses show that olivine is markedly inhomogeneous (Fa<sub>23.7</sub>±9.8Fo<sub>76.4</sub>±8.2 mol. %; Fe/Mn = 132.9, n = 12) in both PO and POP chondrules; orthopyroxene in chondrules grains and in matrix displays a wide compositional variation (Fs<sub>13.9</sub>±7.2En<sub>84.8</sub>±5.4Wo<sub>1.3</sub>±0.1, Fe/Mn = 86.9, n=13), High-Ca pyroxene has a diopsidic composition (Fs<sub>9.6</sub>±1.6En<sub>42.6</sub>±0.9Wo<sub>47.7</sub>±0.4, n=5). Feldspar is albitic (An<sub>15.1</sub>Or<sub>4.9</sub>). Oxygen isotope analyses provided the following results: δ<sup>17</sup>O = -2.463‰, δ<sup>18</sup>O = -1.607‰, Δ<sup>17</sup>O = -3.30‰.

Textural, compositional data suggest a classification as carbonaceous chondrite, belonging to the CV clan (CV3); this hypothesis is confirmed by oxygen isotope data (Clayton & Mayeda, 1999; Gattacceca et al., 2020; Greenwood et al., 2000, 2010; Schrader et al., 2011; Young & Russel, 1998).

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## Optical Tweezers: Evaluating their analytical potential for space sample-return missions

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Keywords: optical tweezers, planetary dust and sample return mission.

Based on highly focused laser beams, optical tweezers are novel tools enabling contactless, non-invasive trapping and manipulation of particulate matter in different media including liquids, air and vacuum. Coupled with Raman spectrometers, optical tweezers allow high-resolution (i.e., no background noise from substrate) spectroscopic analysis of physico-chemical properties of dust grains. Although in recent years they have been widely and successfully used in a variety of research fields (Jones et al., 2015), their application in space science is in its infancy (Alali et al., 2020, Polimeno et al., 2021).

In principle, optical tweezers have key prerequisites for maximizing the scientific return from the analyses of planetary dust samples collected by the current and future sample return missions (e.g. Hayabusa-2, OSIRIS-Rex, Mars 2020; Chang'e 5), particularly during the preliminary investigation procedures in receiving/curatorial facilities (e.g. Smith et al., 2021). High-resolution, contactless and non-invasive analyses of planetary dust are actually expected to provide unprecedented information on the astrophysical origin and geologic evolution of their parent bodies. They are also expected to be instrumental for biohazard assessment for constrained sample return missions – like those targeting Mars or the icy bodies in the outer solar system, and the detection of past or extant extraterrestrial life.

Optical tweezers, developed in our laboratories (Gillibert et al., 2019), were used to collect individual dust grains from powdered analogues and extraterrestrial materials (e.g. carbonaceous chondrites and lunar regolith; Collareta et al., 2016) of known composition and to determine their composition and response to optical forces without substrate effects. Results document the high potential of this novel technique and will be used to assess its effectiveness in the micromanipulation and analysis of extraterrestrial dust from space sample return missions in receiving/curatorial facilities and its potential role within coordinated multiscale analytical protocols.

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***Ab-initio* modelling of Fe<sub>2</sub>NiP-H<sub>2</sub>O interaction: a phosphate factory for Early Earth**Pantaleone S.<sup>\*1-2</sup>, Corno M.<sup>1</sup>, Rimola A.<sup>3</sup>, Balucani N.<sup>2-4-5</sup> & Ugliengo P.<sup>1</sup><sup>1</sup> Dipartimento di Chimica and Nanostructured Interfaces and Surfaces (NIS) Centre, Università degli Studi di Torino.<sup>2</sup> Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi di Perugia. <sup>3</sup> Departament de Química, Universitat Autònoma de Barcelona, Catalonia, Spain. <sup>4</sup> Osservatorio Astrofisico di Arcetri, Firenze. <sup>5</sup> Université Grenoble Alpes, CNRS, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), Grenoble, France.Corresponding author e-mail: [stefano.pantaleone@unito.it](mailto:stefano.pantaleone@unito.it)

Keywords: Meteorites, phosphorus problem, DFT, prebiotic chemistry.

Phosphorus is ubiquitous in planet Earth and plays a fundamental role in all living systems. Finding a reasonable prebiotic source of phosphorus is not trivial, as common sources where it is present nowadays are in the form of phosphate minerals, which are rather insoluble and non-reactive materials, and, accordingly, unavailable for being readily incorporated in living organisms [1]. A possible source of phosphorus is from the exogenous meteoritic bombardment and, in particular, in iron/nickel phosphides [3,4,5]. These materials, by simple interaction with water, produce oxygenated phosphorus compounds, which can easily react with organic molecules, thus forming C-O-P bonds [6,7]. It has been estimated that up to 10% of the early Earth crust was composed by phosphide minerals, after the heavy meteor bombardment, and that many tons per year of phosphorus oxygenated compounds have been produced [8]. In the present work, periodic ab-initio simulations at PBE level (inclusive of dispersive interactions) have been carried out on Fe<sub>2</sub>NiP-schreibersite, as a relative abundant component of metallic meteorites, in order to characterize structural, energetics and vibrational properties of both bulk and surfaces of this material [9]. Moreover, also the interaction with water was analyzed, modelling both high and low coverage regimes, in order to study the corrosion process which ultimately leads to the production of phosphorus oxygenated compounds, like phosphites (HPO<sub>3</sub><sup>2-</sup>/H<sub>2</sub>PO<sub>3</sub><sup>-</sup>) and phosphates (HPO<sub>4</sub><sup>2-</sup>/H<sub>2</sub>PO<sub>4</sub><sup>-</sup>).

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## Water in the inner Solar System: insights from achondrite meteorites

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One of the major unresolved questions in the field of cosmochemistry is to understand the source(s) and timing of water delivery into the inner Solar System and more specifically to the Earth. The major volatile elements hydrogen (H), carbon (C) and nitrogen (N) are commonly thought to have been delivered to Earth via a late influx of carbonaceous chondrite (CC) type objects originating from the outer Solar System, based on H and N isotope similarities with CCs (Alexander et al., 2017). However, the discovery of chondrite-like water in achondrites, i.e. eucrites (Sarafian et al., 2014) and angrites (Sarafian et al., 2017), whose parent bodies formed only few Ma after calcium-aluminium-rich inclusions (CAIs) (Wadhwa, 2008) - the oldest solid objects in the Solar System - implies that either the water was brought earlier to the inner Solar System than envisaged (so called 'dry' scenario) or achondrite parent body, like 4Vesta, accreted water earlier from a common reservoir that subsequently supplied water and other volatiles to the Earth.

In order to resolve the timing and source(s) of water in the inner Solar System, we analysed hydrogen concentration and isotopic composition in nominally anhydrous minerals (NAMs), i.e. olivine and pyroxene, as well as in phosphates, of a range of achondrites sampling the first few Ma of the inner Solar System history. Primitive to differentiated achondrites were selected, i.e. acapulcoites-lodranites, representing the best examples of a partially differentiated asteroid; and eucrites, thought to originate from the asteroid 4Vesta. So far, phosphates and NAMs from eucrites were measured using the Cameca NanoSIMS 50L at the Open University (Stephant et al., 2021). The hydrogen isotopic composition of Stannern, Juvinas and Tihert clinopyroxenes revealed a D-poor hydrogen isotopic composition for the asteroid 4Vesta ( $\delta D = -373 \pm 127\%$ ), lighter than the Earth and CC values, suggesting that 4Vesta and possibly other inner Solar System bodies may have accreted some nebular hydrogen.

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**S24.**

**The contribution of geology to the knowledge of solar system  
bodies**

*CONVENERS AND CHAIRPERSONS*

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## Tectonic styles of the Martian crust: insights from Cerberus Fossae and Thaumasia Highlands

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*Keywords:* Mars, tectonics, morpho-tectonic structures, swarm, topographical profiles, kinematic numerical modelling.

The tectonic styles that affected the Martian crust are still open debated. We consider the Martian topography as a reference surface where the long wavelength morphology (tens of km) is likely related to some type of tectonic activity. We explore the regional tectonic setting by a) mapping of regionally sized structures and b) numerical modelling of regional topographic profiles. a) We manually map the morpho-tectonic structures that exceed one order of magnitude the average Martian crustal thickness (Neumann et al., 2004,  $L \geq 450$  km) between 60°N and 60°S. The mapping is based on photo-geologic interpretation of enhanced satellite image mosaic belonging to different datasets, which describe both the topography (Viking, MOLA) and the thermo-physical properties of the outcropping lithologies (THEMIS). We statistically analyse the mapped structures to explore their clustering into azimuthal families called swarms and described in terms of spatial distribution, length, spacing, sinuosity and self-similar clustering. The preliminary results of our mapping show that i) the Cerberus Fossae in the Lowlands and the Sirenum Terra in the Highlands are characterized by swarms with similar morphologies and that ii) many structures are characterized by en-echelon pattern that strongly suggest a strike slip component in addition to the mainly extensional setting described in literature. b) To better characterize some key structures, we analyse across-strike topographical profiles of regionally sized morpho-tectonic depressions in the Thaumasia region where a dense net of nearly parallel scarps and troughs crop out and have been interpreted as a possible rift-like system (Hauber & Kronberg, 2005). Our kinematic numerical modelling allows to replicate the observed morphologies as the result of the relative movement between hangingwall and footwall crustal blocks separated by fault with given geometry and displacement. The modelling is based on the HCA method (Salvini & Storti, 2004) which was successfully used to simulate tectonically controlled morphologies on Earth in negligible erosional environments. Results can provide important constraints to better understand the tectonic styles that affected Mars (thick skinned/steep-planar faults vs thin skinned/listric faults).

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## Comparison of emissivity spectra from Mars surface and laboratory rock samples: preliminary results

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*Keywords:* TES, infrared, terrestrial planets, geochemical features.

The spectral characterization of planetary surfaces and other solar system objects allows us to obtain geochemical information useful for geological mapping and for understanding the evolutionary history of planets and other celestial objects. Furthermore, identifying planetary surfaces geochemical properties, allow us to characterize volcanic features in order to investigate new volcanic mechanism anomalous on planet Earth, but common in other places. The goal of this work is to geochemically characterize planetary surfaces, through the investigation of their mid-infrared range spectra. We propose a spectral characterization of geological properties by means of comparison between planetary surfaces emissivity spectra, measured by probes, and analog rock samples emissivity spectra, measured in laboratory, obtained from natural melting samples. Principal component analysis, clustering and categorization machine learning algorithms and statistical methodology are utilized to spectral comparison as well as spectral data analysis. These techniques allow us to analyse a large amount of data. We have analysed about 1000 emissivity spectra of a Martian basaltic lava flow located at west of Arsia Mons (3° S, 221,8° E, IAU 2000), at the T=273-300K; about 500 emissivity spectra of Nili Patera, a Martian caldera situated to Syrtis Major Planum (9° N, 67° E IAU 2000), at T=273-300K; both groups measured by Thermal Emission Spectrometer (TES) onboard NASA's Mars Global Surveyor. Regarding our sample spectra, we have analysed 11 emissivity spectra of samples synthesized at the UNIPG laboratory, measured in reflectance and emissivity at the temperatures of 450, 600, 750 and 900K; other 80 emissivity spectra of rock samples from dataset of the Arizona State University were also analysed. On Mars, magmatic differentiation is present, as occurred in Nili Patera caldera, where THEMIS multispectral images show an evident spectral contrast due to magmatic differentiation. The same contrast is identifiable in our TES spectral analysis. The preliminary results show similar trend for chemical component that we have been analysed. Once chemical and spectral features of our samples will be better characterized, we will be able to define quantitative geochemical constraints in order to make geological maps based on mid-infrared measures.

## Aqueous alteration of layered deposits within Sera and Jiji, Mars

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**Keywords:** paleoclimate environments, aqueous alteration, martian deposit, mars, layered deposits.

Martian Equatorial Layered Deposits (ELDs) reveal interesting and crucial aspects of ancient geological conditions and are useful to reconstruct the paleo- climate and environmental setting. Their origin is still debated as well as the putative paleoenvironmental setting in many areas on Mars (Andrews-Hanna & Lewis, 2011; Pondrelli et al., 2011; Zabusky et al., 2012; Kite et al., 2013; Lewis & Aharonson et al., 2014; Cadieux & Kah, 2015; Annex & Lewis, 2020). To better constrain their formation and paleoenvironment, we analyzed the morphology, stratigraphy, and mineralogy within two craters in close proximity to each other in Arabia Terra, Sera and Jiji. ELDs within those craters are characterized by hydrated sulfate signatures implying a certain amount of water activity. Layer attitudes show folds with collinear axial traces trending NW – SE, whereas thinning and thickening sequences show shared and repeated changes in the depositional environment from high to low energy in both craters. The Loess Plateau China is a possible terrestrial analog for the deposition of the ELDs in these craters. Furthermore, the existence of isolated layered mounds suggests a post-depositional formation process involving repeated water level rises and areas of differing capillary forces. Our study contributes to the understanding of regional geological processes in Arabia Terra and reveals long term aqueous activity, which as a result, impacts the ongoing discussion of ELD association with potential biosignatures.

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## **A Volcano-tectonic activity: possible scenario beyond the formation of the rift systems in Noctis Labyrinthus (Mars)**

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*Keywords:* bidirection, extension, rifting, troughs, pit-chains, tectonic, Noctis Labyrinthus.

Noctis Labyrinthus is located in the western part of the large extensional province of Valles Marineris and close to the vast volcanic plateau of Tharsis Montes. Within this area, linear pit-chains commonly occur in close vicinity to faults, inside the graben, and mainly connected to swarms of small cracks, generating a complex pattern of interconnected faults and a widespread grid of scalloped pit-chains. Such a striking spatial correlation between faults and pit-chains makes this area a location of interest to study the possible mechanisms of formation and evolution of these features. Previous work interpreted Noctis Labyrinthus as a karst landscape with associated caves and water-related processes, a network of lava tubes or the result of volcano-tectonic activity (Mège et al, 2003, Schultz, 1998).

In this work, we used two orthoimages acquired by the High-Resolution Stereo Camera (HRSC), bearing a resolution of 12.5 m/pixel, and for the surface topography, we utilized an individual Digital Elevation Model (DEM) from Mars Orbiter Laser Altimeter (MOLA), with a resolution of ~460 m/pixel. We have mapped all apparent faults and grabens within the selected area (N=3781). Each fault was traced by a single polyline or by a group of polylines when segmented, and we distinguished their size by assigning different colors, while the pit-chains were delimited by a polygon shapefile. We performed a detailed analysis of the fault's patterns and geometries over different lengths with the aim to provide a comprehensive model for the formation of the complex structural features in Noctis Labyrinthus.

The azimuth distribution of fault populations shows two main trends in the rose diagrams: ENE-WSW and NS. The NS faults systems are apparently crosscut by the ENE-WSW faults system, which seems to occur before pit chains formation. We infer a development of two fault systems potentially produced in response of bidirectional or radial extension, where distinct faults develop perpendicular to each extensional direction. The extension is driven by invariant regional stress field, in pure shear, where faults grow at different scales.

We propose that a Synchronous or 2-Phase bidirectional regional extension can be the prime processes behind the formation of the rift systems in Noctis Labyrinthus and the generation of T, L, and X-Shaped intersections between faults. The presence of pit chains remains difficult to explain within this setting: the interaction with magmatic activity from the large nearby Syria Planum magmatic complex might have played a role in shaping these structures. In this scenario, dikes intruded below the graben floors might have exploited the local extensional setting creating dilatant conditions in correspondence of major structures. A subsequent pressure drop in the plumbing system might have led to a surface collapse forming the large pit chains.

## Mapping the regional tectonic asset of the Discovery quadrangle of Mercury

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*Keywords:* Mercury (planet), structural analysis, planetary tectonics, planetary geological mapping.

The Discovery quadrangle of Mercury (H-11) located in the area between 22.5°S–65°S and 270°E–360°E encompasses structures of paramount importance for understanding Mercury's tectonics. The quadrangle is named after Discovery Rupes, a NE-SW trending lobate scarp, which is one of the longest and highest on Mercury (600 km in length and 2 km high). By examining the existing maps of this area (Trask and Dzurisin, 1984; Byrne et al., 2014), several other oblique trending structures are visible. More mapping detail could be achieved by using the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) Mercury Dual Imaging System (MDIS) imagery. We aim at mapping the structures of H-11 at high-resolution by using MESSENGER/MDIS basemaps, in order to understand its regional tectonic history by following the work done in the Victoria quadrangle (H-2) (Galluzzi et al., 2019). Differently from H-2, located in the same longitudinal range but at opposite latitudes, this area lacks in N-S trending scarps, such as the Victoria-Endeavour-Antoniadi fault system, which dominates the northern hemisphere structural framework. The existing tectonic theories predict either an isotropic pattern of faults (global contraction) or an ordered distribution and orientation of faults (tidal despinning) for Mercury. If we expect that the existing tectonic patterns were governed by only one of the two processes or both together, it is difficult to understand how such different trends formed within these two complementary areas. The structural study done for H-2 reveals that the geochemical discontinuities present in Mercury's crust may have guided and influenced the trend and kinematics of faults in that area (Galluzzi et al., 2019). In particular, the high-magnesium region seems to be associated with fault systems that either follow its boundary or are located within it. These fault systems show distinct kinematics and trends. The south-eastern border of the HMR is located within H-11. Hence, with this study, we aim at complementing the previous one to better describe the tectonics linked to the presence of the HMR. Furthermore, this geostructural map will complement the future geomorphological map of the area and will be part of the 1:3M quadrangle geological map series which are being prepared in view of the BepiColombo mission (Galluzzi, 2019).

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## Dome-sulcus interactions within Melkart crater on Ganymede

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*Keywords:* Central-dome craters, Strained craters, Ganymede, Icy Satellites.

Melkart is a complex central-pit-and-dome crater with a diameter of 103 km located in the southern Marius Regio of Ganymede. Although Marius Regio is characterized by old dark terrains, Melkart crater formed on top of a bright and recent sulcus that branches with NW-SE direction from the southern WNW-ESE Sippar Sulcus. The geological asset of both Melkart and the underlying sulcus can provide important information on the mode of formation of the crater and its central dome. For this reason, we produced a 1:1,000,000 geological map of Melkart using NASA Galileo Solid-State Imaging frames of ~180 m/pixel to analyze the relationship between the dome units and the fractures characterizing the whole central pit area. The fracturing is pervasive across the central pit units and the structural analysis of the fractures, done by means of rose diagram analysis, reveals a prominent NW-SE systematic alignment. This preferential orientation well corresponds to the orientation of the underlying sulcus. Hence, the dome fractures inherited the sulcus preferential orientation and the sulcus might have been still active at the time when the dome formed (i.e., syntectonic impact). Moreover, by analyzing the crater's ellipticity we observe a larger diameter in the E-W direction. Thus, the strained diameter is possibly the result of both the unnamed underlying sulcus, opening in the NE-SW direction, and the larger Sippar Sulcus, opening in the NNE-SSW direction. Hence, this site provides evidence of transtensional deformation on Melkart crater in its early stage, as also observed for later stages of deformation on other craters cross-cut by sulci on Ganymede. Although an impact-related rim elongation has a low probability of being oriented exactly in the direction where the tectonic deformation is expected, further analyses are being made on the ejecta distribution to evaluate this case also. Results from this study will be helpful for refining the observational strategies of the JANUS camera onboard the ESA JUICE mission.



## Geological sites of interest in Kuiper quadrangle (H06): an integrated analysis between morphological and spectral characteristics

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*Keywords:* Mercury, planetary mapping.

Kuiper quadrangle (H06) is located at the equatorial zone of Mercury and encompasses the area between longitudes 288°E – 360°E and latitudes 22.5°N – 22.5°S. A detailed geological map (1:3M scale) of the Kuiper quadrangle based on the MESSENGER Mercury Dual Imaging System – Narrow Angle Camera (MDIS-NAC) high spatial resolution data, was performed by Giacomini et al., 2018.

The main basemap used for H06 mapping was the MDIS (Mercury Dual Imaging System) 166 m/pixel BDR (map-projected Basemap reduced Data Record) mosaic. The geological map showed that the quadrangle is characterized by a prevalence of crater materials. Some of which, in the MDIS global color mosaics (Becker et al., 2009; Denevi et al., 2016), show bright regions within their floor. In this work, we took into account some of these craters to study in more detail, both by a morphological and a spectral point of view, in order to create an integrated geological map. To reach this aim we used a spectral map of H06, achieved by MDIS WAC data. In particular, we produced mosaics at 385 m/pixel and 246 m/pixel covering the areas of interest (Carli et al., 2020). By using these products the spectral variations, highlighted by specific indices and color combinations, are discussed in order to define spectral units to be integrated with the morpho-stratigraphic ones. This analysis allowed us to infer some indications on material composition as well as to produce a more detailed geological map for the study areas, where morpho-stratigraphic and spectral units are integrated to each other. This preliminary analysis highlighted that a higher spectral and spatial resolution are needed in order to obtain new information about the origin of the landforms and deposits. In light of these evidences, it appears that the high resolution of the instruments of BepiColombo mission, like STC and HRIC cameras and VIHI spectrometer of SIMBIO-SYS, can significantly contribute to answer several questions raised during the geological mapping and analysis of the Kuiper quadrangle.

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## Geologic map of the Beethoven Quadrangle (H07), Mercury

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*Keywords:* Planetary geology, Mercury, Beethoven quadrangle, Geological mapping.

A new 1:3M-scale geological map of the Beethoven Quadrangle (equatorial latitude), covering an area of ~6M km<sup>2</sup> (7,7% of the total Mercury surface), has been compiled exploiting MESSENGER data. This work is part of a global series of 1:3M-scale geological maps of Mercury, prepared in support of the ESA/JAXA BepiColombo mission to set up the context for mission operations and help re-define the mission goals. The mapping has been performed within a GIS environment and operated on a georeferenced monochromatic basemap at 166 m/pixel resolution (BDR, map-projected Basemap reduced Data Record). In support of mapping, we also used the Mercury Laser Altimeter (MLA) DTMs, several basemaps with different incidence angles, and color global mosaics. We distinguish crater materials and plains units. According to their overlapping relationships and degree of morphological preservation, craters with D>20 km and their related materials are distinguished into three morpho-stratigraphic classes (from the more degraded c1 to the freshest c3). The plains units are classified as smooth, intermediate, and intercrater plains materials (Schaber & McCauley, 1980). Based on the dominant contractional features affecting Mercury (Byrne et al., 2014), tectonics structures are interpreted as thrusts, when they show a relevant break in slope and lateral continuity or are mapped as wrinkle ridges when the break is less evident and is limited to smooth plains and basins. The SW sector of the quadrangle is floored by half of the Beethoven basin, one of the largest (D ~ 630 km) basins on Mercury of the late Tolstoian period (3.9 Ga). Similar to other large basins on the planet (e.g., Caloris and Rembrandt), we distinguished units specific to the Beethoven impact basin. Its floor is covered by volcanic smooth plains materials, and its ejecta are mapped as Brm (Beethoven rim materials), defined as hilly and radially lineated material, extending outside of the rim of the basin.

The new geologic map represents a more detailed cartographic product with respect to the previously released 1:5M map of the quadrangle (King & Scott, 1990) and will contribute to improving our knowledge of the planet's stratigraphy and surface history.

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## **The Apollo Lunar Exploration Program: how Increasing Science Capabilities Resulted in a Revolutionary New View of the Moon**

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*Keywords:* Apollo, Moon, NASA.

There has been no other mission or mission program that has more fundamentally changed our way of understanding space than the Apollo Lunar Exploration Program. The first human landing on an extraterrestrial body, the first in-situ study by a trained geologist. The first sample return, the first extraterrestrial seismic experiment and network, the first extraterrestrial heat flow measurement, and dozens of surface experiments, to name a few. Project Apollo landed six lunar modules and twelve astronauts on the Moon between July 1969 and December 1972 to explore and undertake scientific exploration traverses. It returned 382 kg of lunar samples and a wealth of data that are still intensely explored today. As examples we note that only a few years ago application of modern seismic data analysis tools to the historic Apollo seismograms have revealed what are arguably reflections of waves from the lunar core. Moreover, traces of water have recently been found in re-analysis of lunar samples. In this presentation we will discuss how the scientific input and science and engineering synergism during the Apollo Lunar Exploration Program resulted in ever-increasing capabilities to visit a wide range of landing sites on the Moon and to conduct geological traverses that culminated in the Apollo 15-16-17 Scientific Expeditions to the Moon. Each succeeding Apollo mission was characterized by increasing exploration capabilities (landing accuracy, stay time, EVAs, mobility, experiments, tools, etc.). We present a brief review of the landing sites, surface operations and science return of each succeeding Apollo mission and show how science and engineering synergism resulted in a rapid transition from achieving a national goal (Apollo 11) to sophisticated scientific expeditions targeted to areas critical to understanding the origin and evolution of the Moon. The Apollo Exploration program resulted in an entirely new paradigm for the origin and evolution of the Moon, and indeed, other planets. Lessons for future human and robotic exploration, including NASA's Artemis Program, will be described.

## Cratering Record and Age Dating of the Galilean Satellites

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Keywords: Ganymede, crater database, chronology.

JUICE, JUPiter ICy moons Explorer, the ESA mission planned to be launched in 2022 and to arrive at Jupiter in 2029, will make detailed observations of Jupiter and three of its largest moons. One of its goals is to improve the current estimates of Ganymede surface age. Ganymede, observed by Voyager 1 and 2 in 1979, and Galileo from 1996 to 2000, revealed a surface with two main types of terrains, differing in albedo, crater density, and surface morphology (e.g., Patterson et al., 2010). The first one, the “dark” terrains, is low albedo terrains, covered by regolith material, and heavily cratered. The second one, the “light” terrains, has higher albedo and lower crater density, suggesting a younger age. They can occur as smooth elongated and polygonal shaped areas, or as grooves. An accurate chronology for Ganymede can therefore provide information about resurfacing and the evolution of the surface, including the extent of the cryovolcanism (Pappalardo et al., 2004).

The goal of this work is to improve Ganymede crater chronology using the most updated understanding on the current and historical impact flux resulting from recent dynamical models. We will present our results in improving the geological mapping of the Ganymede surface, and deriving a revised crater database for Ganymede. Crater counting is performed by selected impact structure by means of photo-interpretation (e.g., primary vs secondary, etc.) in areas of Ganymede acquired at the highest resolution (<100 m/pixel).

The precision of crater counting is crucial to derive reliable age estimates. Factors affecting the shape of the crater size–frequency distribution are: contamination due to secondary craters and/or volcanic structures; ejecta blanketing; superposition, abrasion, and infilling; image resolution; and illumination conditions. We quantitatively estimate the accuracy of our counts by selecting sub-areas for which we have images available also at a spatial resolution better than a factor of five. We made there a second additional count, and made a direct comparison of the craters counted in these sub-areas when using either the image at lower or higher resolution. We found that craters counted in the low resolution images are often larger than the true value, due to a poor identification of the crater rim. Moreover, we marked as primary a number of crater-like features, which display a circular shape with an inner shadow in the low resolution image, but they then turn out to be an erroneous detection when cross-checking in the high resolution image.

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## Mappy: a python plugin to ease geological mapping with QGIS

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Keywords: geological maps, QGIS, GMAP project.

Geological maps have been historically a central part of the geological knowledge acquisition process: they are used to summarize all the relevant information of a site of interest and they provide a subdivision of an area into geological units.

In its simplest form, a digital geological map produced in a Geographical Information System (GIS) typically takes the shape of a polygonal layer, which is needed to visualize the map. For this reason, it is quite common that mappers start new maps by populating a polygonal layer. Although this approach is easier to understand, it inherently has several drawbacks. In particular, the mapper will draw a contact twice for each neighboring polygon, resulting in the need of specialized topological editing tools. Furthermore, the contacts should be stylable (e.g., to represent how much certain we are about the contact). This is not possible with a polygonal representation alone and would require duplicating those contacts as an additional layer, which will, in turn, require additional editing whenever the map is updated.

The solution to these issues requires adopting a different approach to avoiding data duplication inherent in a polygonal representation. We hereby present a python plugin for the popular QGIS software, which helps mappers adopt a more topologically-safe approach.

Mappy expects its input to be constituted by lines, representing the geological contacts. Provided the lines intersect each other, these suffice to define the partitioning of the map in different units. To assign to each region additional information (i.e., unit's names) a point layer, containing the needed attributes, is used. Mappy then takes care of updating a polygonal layer by generating the polygons and merging the attributes.

This approach, similar to the one suggested by Skinner et al. (2018) has several benefits: any number of segments can be used to define a contact, making it possible to assign different attributes to different portions of the same line. The maps are easier to edit because any time a contact is modified the changes will automatically propagate to all affected polygons, without resorting to specialized topological editing tools. Furthermore, the contacts can be reused for map layout and directly styled. In this way, the mapper can draw the contacts working on just two units at a time, and the map can be progressively refined with no significant effort.

These ideas can be implemented in any GIS of choice by performing a polygonization of the contacts and a spatial join of the points to assign the attributes, or Mappy can be used. Mappy enables the operator to adopt a polygons-free strategy during the whole creation of the map and provides the algorithms needed to re-generate the polygonal layer at any time. It also comprises additional tools for clipping the contacts at the intersection points and for automatic placement of the points. Once the base layers are created (points and contacts) Mappy will update the resulting polygonal layer automatically, which style can be defined progressively during the creation of the map.

Mappy has been already tested during the PLANMAP-GMAP mapping winter school, simplifying the generation of consistent geological maps to the students, and demonstrating the benefits of this approach, especially for newcomers which were able to produce new maps without the need of understanding complex topological editing tools.

This tool will be further developed to support the upcoming mapping efforts during the JUICE mission, ESA ExoMars, and other missions interacting with the GMAP project.

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### 3D geo-model of Rembrandt basin on Mercury: structural framework and infilling

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*Keywords:* Mercury, 3D geologic model, Rembrandt basin, thrust, volumes, impact basin.

Rembrandt, a 715 km-diameter basin on Mercury centered at 32.89°S, 87.86°E, constitutes a remarkable example of the stratigraphic variability on Mercury. The uppermost smooth plains of volcanic origin have been distinguished by the surrounding smooth plains utilizing spectral information. Moreover, it is crosscut by a thrust system more than 1000 km long with NE-SW orientation. It is a set of lobate scarps and wrinkle ridges with inverse to transpressional kinematics (Massironi et al., 2015), named Enterprise Rupes (Ferrari et al., 2015; Galluzzi et al., 2015; Semenzato et al., 2020). Its formation is attributed mainly to crustal shortening induced by global contraction (see Semenzato et al., 2020 and references therein).

The aim of this work, as part of the PLANMAP Horizon 2020 project, is to use all the available geologic information to construct a 3D model of both the structural setting and the thicknesses of the main units of the Rembrandt basin infilling.

We based our reconstruction on the geo-stratigraphic map and geologic cross-section of Rembrandt basin from Semenzato et al. (2020). Additional constraints, regarding fault kinematics and fault plane geometry were derived by Galluzzi et al. (2015) and Crane (2020). As a basemap, we used the MESSENGER MDIS global mosaic at 166 m/pixel together with the MDIS global DEM (665 m/pixel). The base unit of Rembrandt (named IT - para-autoctonous intracrater plains) is overlaid by two different events of infilling: the YIP (Young Interior smooth Plains) and OIP (Older Interior smooth Plains) units. Their thickness was estimated in Semenzato et al., (2020). We built 14 cross sections that were subdivided into two intersecting sub-parallel sets. The interpreted subsurface horizons were used for mesh interpolation together with the geologic contacts between the different units on the surface creating the top of the YIP, OIP and IT units.

The volume between them was then calculated by means of a tetrahedral mesh. The structural modelling was also carried out on the basis of Semenzato et al., (2020) and Ferrari et al., (2015). The faults' vergence and their angles were extracted thanks to the illumination conditions on the image mosaic, and also to the measurements provided by Galluzzi et al., (2015), Crane (2020) and Massironi et al., (2015). The Enterprise rupes thrust geometry was constructed including its splays and backthrusts, as well as the contractional lobate scarps and extensional radial features within the basin units.

We show that also with relative scarcity of data, the 3D geomodelling proves to be a useful tool in order to derive new information on subsurface geology. Further work will focus on forward and backwards modeling of the Enterprise Rupes system.

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### 3D geo-model of Uruk Sulcus structures (Ganymede): insights and implications

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*Keywords:* Ganymede, 3D modelling, icy satellites, ice volumes, fracture network, structural geology, transpression.

The surface of Ganymede appears as a deeply tectonized environment mainly composed of a brittle icy crust overlying a subsurface global liquid ocean, whose depth was constrained to be between 100 and 150 km. The surface of Ganymede can be subdivided into dark and bright terrains depending on their crater density, differences in albedo and surface morphology. The terrains can be subdivided according to the presence of furrows or grooves that represent the brittle deformation of the satellite's icy shell. The study area is between 150W -180W and 30N-10 S in the region of Uruk Sulcus, a NW-SE terrain ~400 km wide and ~2500 km long. Its origin is attributed to a major dextral transpression (Rossi et al., 2020) and it was shown that the spatial distribution of such structures shows a fractal spatial clustering, implying that the fracture network below the surface can be interconnected and percolating, reaching up to the ~100-150 km-deep ocean (Lucchetti et al., 2020). To better constrain the transpression hypothesis in Uruk Sulcus, we are testing different 3D geomodelling approaches to derive more information on both the volume of the fractured brittle ice crust and the most favored location for percolation.

At present day, 3D geolocal modelling is approaching the planetary geology, as also testified by the outcomes of the PLANMAP Horizon 2020 project (Massironi et al., 2021; Pozzobon et al., 2021).

A preliminary model of Uruk sulcus was built using the global DEM by Zubarev et al., (2017) as an upper surface boundary to project the structural mapping from Rossi et al., (2020) and then textured with the controlled global mosaic at an average resolution of 359 m/pixel. As a lower model boundary, the icy crust is constrained at depth by the ocean-ice interface. In particular, we used the depth value calculated using the fractal clustering analysis in Lucchetti et al., (2020) related specifically to Uruk sulcus. We were able to reconstruct a preliminary qualitative model of the fault geometries for GUS1 (Grooves of Uruk Sulcus 1) system deformation (Rossi et al., 2020) as a large-scale structural framework. We performed a first test on a smaller region. We extracted a voxel-based volume of icy crust in the sigmoidal area named S2 and containing the GUS3 (also in Rossi et al., 2020) comprised between the surface, the lower ocean-ice interface, and bounded by the major fault lines delimiting GUS3. At this location a major set of NE-SW high-angle extensional structures arranged in a right-stepping en-echelon geometry are present together with other two grooves families with NW-SE and NS orientations, although lower in number. By exploiting the voxel-based volume and using the scaling laws that rule of the size distributions of the grooves and their azimuths, it is possible to create a DFN (Digital Fracture Network) for each of the fractures' families and predict possible high-connectivity locations. The 3D geomodelling approach proves to be a promising tool not only for scientific analysis but also to identify interesting targets for future observation with the JANUS instrument (Palumbo et al, 2014) onboard the upcoming JUICE mission.

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## Strike-slip and shortening in the dark terrain of Ganymede

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*Keywords:* Ganymede, tectonics, mapping, planetary geology.

The dark terrain of Ganymede is the oldest geologic unit of the satellite, subsequently crosscut by the youngest light terrain. It shows morphotectonic structures called furrows, which are radial or circumferential troughs bounded by high albedo rims and a lower albedo floor. It is assumed that furrows represent a multi-ring basin formed by an ancient impact crater (McKinnon & Melosh, 1980; Prockter et al., 2000). In fact, Galileo Regio's furrows show a concentric pattern centered at around 20° S 180° W, which is the assumed location of the crater (Prockter et al., 2002; Hirata et al., 2020). Most of them have been preserved in their pristine form, while some have acted as zones of weakness and have been re-used by later tectonic deformation. These zones are likely considered as precursors of grooved terrain formation. In this contribution, we present the structural mapping at the regional scale of the furrows in Galileo Regio, and we identify their hierarchy and tectonic setting originated by strike-slip and shortening. Riedel shear, synthetic and antithetic structures, and conjugate fractures have been identified. Hence, the performed mapping allows to infer the tectonic setting of the furrows and their associated structures, and in turn the (paleo)stress field that affected the area. Galileo Regio has been deformed by the same regional kinematics consistent with the right-lateral transpression that has affected Uruk Sulcus (Rossi et al., 2018). We infer a  $\approx$  NE-SW trending maximum horizontal stress responsible for a shortening associated with strike-slip in the area extending from 180°-120° W to 0°-60° N. This work confirms the key role that transpression has played in the leading hemisphere of Ganymede and further statistical analysis will be performed to support this reconstruction. The produced tectonic model will be used for the scientific preparation of future high-resolution observation that will be performed by the JANUS instrument onboard JUICE mission (Palumbo et al., 2014).

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## Search for geologically young areas on asteroid surfaces using the phase-ratio method

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*Keywords:* Asteroid Vesta, Dwarf Planet Ceres, regoliths, phase-ratios, image processing.

The phase-ratio method is a tool for evaluating the optical roughness of the lunar regolith. The slope of a brightness phase function  $f(\alpha)$  of a regolith-like surface strongly depends on its albedo and texture. For suppressing the influence of the albedo variations over the surface in this method it is needed to find the ratio of two images of the same region acquired at different phase angles  $\alpha$ . The resulting phase-ratio image contains information mainly on the structural properties of the regolith. Reliability of this method has been proved by the detections of photometric anomalies related to structure variations of lunar surface layer in the spacecraft landing sites [1]. For robust results this method requires space imaging with high spatial resolution (meters per pixel) that are coregistered with sub-pixel accuracy, a topography map with the same (or higher) spatial resolution and a wide range of illumination/observation geometries. Space images which satisfy these conditions were absent for asteroids before the NASA Dawn mission [2]. NASA Dawn spacecraft explored asteroid (4) Vesta and dwarf planet Ceres, the largest body in the Main asteroid belt. The onboard Framing Camera was equipped with a clear filter and seven narrowband color filters from 0.4 to 1.0  $\mu\text{m}$  [3]. During the mission to Vesta and Ceres a large volume of data at different illumination/observation geometries were obtained with spatial resolution of 20-130 m/pixel. The obtained data allow us to start a detailed investigation of Vesta and Ceres' regolith properties in several selected areas using methods that were successfully applied for the lunar surface [4].

We used a set of calibrated Dawn FC2 images acquired during the HAMO and LAMO phases of the mission from the Planetary Data System (PDS) archive (<https://sbnarchive.psi.edu/pds3/dawn/fc/>). The main selection criteria of image pairs were the following: (1) difference between the phase angles should be more than 20 deg; (2) close values of the solar azimuth and incidence angle; (3) similar spatial resolution of the images. We have applied the phase-ratio method for several regions on Ceres (craters Datan, Oxo, Emesh, Heneb, Ikapati, Yalode, Occator, Ezinu, Xevioso, and Ahuna Mons) and Vesta (craters Antonia, Cornelia, Numisia).

The phase-ratio method has been successfully applied for asteroid surfaces using Dawn FC images of the selected regions on Ceres and Vesta. This method allows us to find geologically young areas of the surfaces of these asteroids.

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## **Development of inflated lava tubes in analogous planetary environments: the case of La Corona system (Lanzarote, Canary Islands)**

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*Keywords:* volcanic caves, lava tubes, Inflation, planetary geology, analogues.

Multidisciplinary efforts are currently boosted by an urgent need to improve our understanding of Earth's lava systems in sight of their future exploration on other rocky bodies of the Solar System.

Among the many structures documented in lava fields, lava tubes are one of the most enigmatic. They constitute a peculiar type of caves dug by molten lava flows. These roofed conducts are very efficient thermal structures enabling channelizing lava transport over long distances. The longest lava tubes are found on volcanic plateau characterised by a gentle slope (<2°) or on volcanic islands (e.g. Hawai'i, Canaries, Iceland, etc.). These structures are easily recognizable from the surface by skylights and collapses on the roof forming pits chains, which allow the reconstruction of the tube path. Due to the similar characteristics of basaltic volcanism on other rocky bodies (e.g. Mars and the Moon), it is expected that lava tubes have similar origins and morphologies to those on Earth. Indeed, analogous conformations of aligned collapses have been seen on the surfaces of Mars and the Moon (Haruyama et al., 2012). This discovery has led to a growing interest as these structures could be suitable sites for future exploration and/or permanent human settlement.

Located in the north-eastern part of the island of Lanzarote (Canary Islands), the La Corona lava tube system with its 7.6 km of total length (~8.9 km of cave development) and 10-20 m diameter is one of the terrestrial largest volcanic cave complexes. Accordingly, to the particular geological context in which it arose, La Corona system is one of the most studied. Indeed, the Canarian archipelago represents both long-term and spatially focused volcanic activity over a poorly mobile tectonic plate [less than ~2 cm/yr, during the last 30 Ma (Gaina et al., 2013)]. This environment identifies the Canaries as one of the best analogues of the Martian one-shell plate volcanism on Earth (Meyzen et al., 2015). What makes this inflated lava tube so interesting is a pyroclastic layer, derived by the initial Strombolian activity of La Corona vent (Carracedo et al., 2013) and interleaved within the lava flows crossed by the tube. The layer follows the tube for at least one-third of its extent and we speculate that it could have been pivotal for the inception of the inflation process. By analogy, similar geological settings could be favourable for the formation of lava tubes on rocky bodies like Mars and the Moon, where weak layers of pyroclastic deposits or fine regolith are thought to be common.

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## Geologic mapping and landing site characterization in Copernicus Crater (Moon)

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Keywords: Moon, planetary geology, Copernicus, geologic mapping, landing site.

In this work we propose the geologic mapping of the Copernicus crater and the characterization of a potential landing site for a rover mission. Moreover, we have selected 68 scientific targets for in situ analyses and sampling, which can answer the ESA's scientific questions about the history and geology of the Moon.

Copernicus Crater is a relatively young impact complex crater, located on the near side and of about 100km indiameter. Studying Copernicus means having the possibility to get information about lunar crust, lunar interior, cratering process, and lunar explosive volcanism as well as constraining the age of a reference stratigraphic plane of the whole Moon, with an important impact on the dating system applied to the entire inner Solar System. Olivine spectral signature was detected (Liu F. et al., 2011), and this can provide information about the lunar crust and mantle.

Absolute-dating Copernicus would improve the lunar chronological curve, used to date surfaces of all the bodies of the inner Solar System, through the crater size frequency distribution. Improving this curve means improving the age estimations of all these bodies. Moreover, this work can assist the foreseen human assisted robotic missions.

As an incremental update of the work performed on Tusberti, (2019) we firstly performed a large-scale geological characterization and mapping of Copernicus crater, using remote sensing techniques, analyzing topographic, imaging and spectral data coming from Lunar Reconnaissance Orbiter (LRO), Selenological and Engineering Explorer (SELENE), and Clementine missions where many interesting features were visible (like cinder cones, vents, melt differentiated, fresh craters and presence of olivine). Therefore, we generated two geological maps, one covering the entire Copernicus crater (at a scale of 1:400000) and one focused on its NW quadrant (scale 1:100000). In fact, by analyzing the topography in terms of slope and roughness we infer that this quadrant could be the best candidate for the landing area. Based on those elaborations and on a preliminary hazard study (following the constraints from Pajola M. et al., 2017), we selected a tentative landing ellipse with in mind the engineering constraints of the now deprecated HERACLES mission and the forthcoming EL3 (European Large Lunar Lander). Moreover, the landing ellipse was selected not only for safety reasons but also because 68 potential sampling sites which are located in reachable areas. These sampling sites are carefully selected in order to fulfill the major ESA questions related to Moon exploration.

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**S25.**  
**Urban Geology and Geomorphology**

*CONVENERS AND CHAIRPERSONS*

*Laura Meelli (University of Perugia)*

*Pierluigi Brandolini (University of Genova)*

*Diego Di Martire (University of Napoli)*

*Domenico Calcaterra (University of Napoli)*

## **Geophysical characterization of Ceppo Lombardo Formation (Po Plain NE of Milan, Italy): new data from passive seismic surveys**

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*Keywords:* Ceppo Lombardo Formation, HVSR, Po Plain, geophysical characterization, seismo-stratigraphic characterization.

The “Ceppo Lombardo Formation” (Riva, 1957) is a collection of Quaternary clastic conglomeratic units outcropping and sub-outcropping in an area of the Po Plain, North to the city of Milan (Italy). Due to the shallow depth and the areal extension of this formation, the geophysical characterization assume a great importance for geotechnical engineering, territory use and local seismic hazard studies. The geophysical characterization of such clastic units shows several and not negligible issues, starting from its great areal extension to the great variability in the cementation and alteration parameters. The main geological, geophysical and geotechnical information about this formation, derive from a great amount of data and studies available from local administration and professional studies, these datasets were not ever integrated to have a more robust geotechnical knowledge. With the aim of a more consistent characterization, we gathered and analysed all available geophysical and geological datasets, resulting from well stratigraphies and geophysical soundings. Additional geophysical surveys were conducted, using the single station passive seismic (HVSR) technique; one single site investigation and two 10-km-long perpendicular transects. New and old geophysical data was integrated with the information from geognostic tests (e.g. core drilling and cutting from well drilling) for an efficient validation, then a statistics study was performed. We present the geophysical methods, the statistical analysis results of vs parameter and several depth maps of its distribution in all study area. The main final results show that Ceppo Lombardo Formation show a well detectable impedance contrast where it overlies units with poor geotechnical characteristics. This formation has also been classified as overconsolidated soil ( $V_s < 500 \text{ m s}^{-1}$ ) with the exception of the Brembo unit that show  $V_s$  values of a seismic bedrock ( $V_s > 800 \text{ m s}^{-1}$ ). Additionally, the great variability output of the HVSR tests, indicate that the top surface has irregular geometry with variable impedance contrasts up to about 30 m depth.

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## Evaluation of anthropogenic sinkhole susceptibility in the city of Naples (Italy) through a presence-only algorithm

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*Keywords:* susceptibility mapping, machine learning, sinkhole, Naples municipalities.

Sinkholes are widespread phenomena on the Earth. Consisting of vertical depressions with chiefly circular shape and a three-dimensional funnel shape (Waltham et al., 2005), their triggering is often associated to dissolution or erosion of geological materials, which leads to underground instability and subsequent formation of the depression. When a sinkhole is generated in an urban area, it can be defined as “anthropogenic” sinkhole (Guarino & Nisio, 2012). Because of the presence of a widespread network of artificial cavities, the city of Naples is one of the urban areas most affected by sinkholes in Italy (Basso et al., 2013). To emphasize and recognize the most prone areas, a sinkhole susceptibility analysis has been carried out. The sinkholes susceptibility map has been produced by using a Machine Learning technique, namely Maximum Entropy (MaxEnt). MaxEnt is a presence-only method that relies on the assumption that the best model to represent the true distribution of an event is the one maximizing the entropy. Maximizing the system entropy means that the best model is the one with the maximum uncertainty about event’s probability of occurrence. This, in turn, implies that the best model has no starting hypothesis and all the combinations of predictor variables can trigger the investigated event (Phillips & Dudik, 2008). To apply such algorithm, a sinkhole inventory is required, and twelve environmental variables have been employed to obtain a more realistic susceptibility map. The results highlight that the most susceptible zones coincide with the historical city center due to the higher presence of cavities and secondary aqueduct and sewer networks. In addition, the highest susceptibility class presents a relatively important extension (4.93%) which consolidates the necessity of studying these phenomena in metropolitan cities like Naples in an effort to help the local administration in finding eventual susceptible areas. The produced map is a first attempt to evaluate the sinkhole susceptibility in the study area by using a Machine Learning technique that takes in consideration the whole Naples municipality.

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## Ancient waters in historical city centers: collectors of multidisciplinary knowledge

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*Keywords:* Urban Geomorphology, Historical Aqueducts, Geotourism.

In Urban Geomorphology one of the most relevant aims is the use of historical sources for the definition of urban transformations as a function of historical geomorphological and hydrogeological processes. The superficial and underground water resources are one of the main parameters which influenced the first settlement of cities. For this reason, tracking the ancient “waterways” can underline the geological and geomorphological parameters of a site location (Melelli et al., 2021). Rivers, springs, historic fountains and washrooms, suggest the links between the urban layout and the superficial arrangement of the hydrographic network. In addition, ancient wells, tanks, aqueducts and the water presence in historical underground artificial cavities are precious parameters for the knowledge of the geological arrangement.

In this study the medieval aqueduct placed in Perugia city (Umbria, central Italy) is proposed as an emblematic example of ancient “waterways”. The aqueduct, realized between 1254 and 1280 has a length of about 4 km and, starting from the mountain reliefs present in the northern part of Perugia, reaches the downtown in the heart of the historical center, ending in the wonderful Fontana Maggiore. After several changes occurred in the XIV century, in 1835 the aqueduct was casted off because of numerous operating problems. In the first half of the XIX century the last section, close to the city center, was turned in a characteristic pensile path, being one of the most particular streets in Perugia.

In this paper the entire track has been traced into a digital path, through a GIS system. Along this line the points of interest related to superficial and underground waters have been included. This information highlights the geological aspects of underground waters. The path is a potential geotouristic route where the cultural and scientific aspects merge for didactic and touristic purposes (Bizzarri et al., 2018; Melelli, 2019).

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## **A quantitative approach for the urban adaptation policy to climate change (SECAP): an application to some geological hazards**

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*Keywords:* climate changes, urban geology, geological hazard.

Consequences of climate change are often more obvious on global scale, but downsizing at regional scale implies a good knowledge of territory, its intrinsic fragility and the urban characteristics. Underlining and predicting trends of climate variables within regional and especially municipal scales to promote adaptation and mitigation strategies is the purpose of the SECAP (Supporting Energy and Climate Adaption Policies). A practical approach to analysing the impact of climate change aimed at driving specific policies and actions on an urban scale is the SECAP template, the official report of the Covenant of Mayors initiative.

Using different methodologies, we have examined various extreme climatic events and climate projections at the regional scale, downscaling to the city of Trieste and other rural areas: the heat waves, the drought, the wildfires, the heavy precipitations, and all the consequences linked, for instance, to the river floods or episodic storm surges combined with the sea level rise.

All projections seem to indicate potential significant variations in intensity of extreme events or frequency during the different seasons from a mid-term/long-term timeframe (2050-2100). The intensification of such extreme events amplifies the effects of sea level rise and the temperature increase on the territory, causing important consequences in terms of geological hazard, such as river flood, coastal flood and landslide, especially in a highly urbanized contexts like the city of Trieste.

In order to quantify the cause-effect relationships requested by the SECAP template, we propose a methodology based on the intrinsic geological characteristics and vulnerabilities of the territory. In the template, the current hazards are considered in term of probability and impact, whereas for the future hazards the definition of the expected change of intensity and frequency, as well as the timeframes are requested. The quantitative approach permits to scale the qualitative “low, medium, high” attributes, too generic as indicators.

For the river flood, the Regional Hydrogeological Planning Plan (PAI) and the risk maps of the Floods Directive have been analysed, parameterizing the hazard in a quali-quantitative way and highlighting the vulnerable areas. For the coastal flood we have superimposed predictive models of inundation of the city to the digital terrain model, quantifying the coastal length involved in the phenomenon. For landslide, we analysed and revised the regional landslides database in terms of the number of landslides compared to the extent of the municipal area and the type of land use.

Finally, for each geological hazard, the effects of the foreseen intensification in extreme events were assessed. The analyses obtained show an increasing trend in these geological phenomena, and in general in risk. These considerations form the basis for the drafting of SECAP and local planning.

### 3D geological model of Bologna urban area: preliminary findings

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*Keywords:* urban geology, 3D geological modelling, subsurface depositional architecture, subsidence, geo-hazard.

This work is part of the Italian national project URGENT (Urban Geology and Geohazards: Engineering geology for safer, resilient and smart ciTies) which deals with the study of the geo-hazard occurrence and the potential effects of climate changes in urban settings, and it is aimed at providing operational strategies to the preservation of Italian relevant cities, such as Bologna. The starting point for the study is the definition of a 3D geological model of the urban area of Bologna, from which all the other model types (e.g., hydrological, geotechnical, etc..) can be derived. The model is based on surface geomorphological data and subsurface stratigraphic data, in particular, the 10m resolution DTM (Digital Terrain Model) and the stratigraphic database (boreholes and CPT data) collected by the Geological Surveys of the Emilia-Romagna Region. These data have been analysed by means of GIS and Leapfrog Works environments, to characterize subsurface geology down to the boundary of the Quaternary continental-marine deposits (varying in the study area, SW-NE, generally from about -50 to -400 m s.l.). The preliminary findings emerging from this work, integrated with ISPRA CARG data (F220, F221) and data from literature (Bruno et al., 2020 and references therein) allow a possible subdivision of the study area in 3 principal domains pertaining respectively, from west to east, to the Reno River (RR) valley, the “relative-high” of Bologna (BH) and the Savena Stream (SA) alluvial fan. These domains, despite the common alluvial nature, show in fact remarkably different geomorphological and stratigraphic features. The RR domain is marked by a quite flat morphology and 2 main thick (> 100m) intervals of amalgamated gravel deposits separated by a 20-30m thick fine-grained layer differently from the BH that displays higher elevations and an almost undisturbed thick sequence (>100m) of fine-grained deposits, whereas the SA domain shows a gentle convex-up morphology with a more heteropic depositional architecture. These differences are important for geotechnical modelling and may have relevant implications for geo-hazards, such as land subsidence. This subdivision in 3 different domains has in fact been compared to the areal distribution and the historical evolution of the observed land subsidence process. For this purpose, both historic maps of vertical ground displacement and InSAR-derived deformation maps were considered, and a more recent survey undertaken by the UniBo spin-off “Fragile” from SENTINEL1 data. This preliminary comparison highlighted a clear relationship between the 3 domains and the deformation field obtained by land subsidence monitoring data.

## **Urban geomorphology as a tool to evaluate coastal variations in historical times. An example from the Italian adriatic coastal cities**

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*Keywords:* urban geomorphology, coastal sites, central Italy.

The geomorphological analysis of town areas is one of the most powerful scientific tools to understand how geomorphological factors might have influenced urbanization. The towns of Rimini, Pesaro, Fano and Senigallia have been studied as examples. Those towns, which are urbanized historical sites on the Adriatic coast of Italy, have been modified over the centuries from the Roman age to the present day in strong relationship with peculiar geomorphological conditions. This analysis is focused on how geographic factors could influence their urban evolutions. The shoreline changes, with consequent coastal variations, are similar for the four towns, whereas the difference of altitude and evolution of the rivers created the main differences among them. The results of the geomorphological analysis can be a strong tool to urban planification and risk management, and can provide a support to the valorization of the sites, by contextualizing urban variations within the natural conditions that have influenced the towns' evolution through time.

## Urban geology and geomorphology of Potenza (Basilicata, southern Italy)

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*Keywords:* seismic amplification, urban geomorphology, engineering geology.

Potenza hilltop town, the chief-town of Basilicata region (southern Italy), is located in the axial-active seismic belt (30 to 50 km wide) of southern Apennines, characterized by high seismic hazard and where strong earthquakes have occurred. The study area is located on a long and narrow asymmetrical ridge SW-NE oriented, delimited along the northern sector by steep escarpments.

Geologically, it is characterized by a sequence of Pliocene deposits with an over-consolidated clayey substratum on top of which a sandy-conglomerate deposit lays, which varies in thickness along both west-east and north-south directions.

The study has been carried out through the recovery and analysis of borehole data and geophysical prospections, realized in the past in the historic center and in the surrounding areas, as well as geomorphological and geological field surveys. Geological (well stratigraphy and survey data), geomorphological, geotechnical (mechanical resistance parameters from laboratory tests) and geophysical data (downholes and refraction seismic for the definition of the Vs30 velocities) have also been implemented in the geodatabase.

The stratigraphic data from drilling made it possible to reconstruct the trend and morphology of the top of the over-consolidated clayey substrate and to better define the thickness of the coverages. These data were fundamental for understanding the distribution of macroseismic damage induced by past earthquakes.

In particular, where the substratum is deeper, the morphological ridge is narrow and high damage levels are also more represented; this sector is characterized by seismic amplification factors, such as stratigraphy (higher thickness of sandy-conglomerate deposits) and geomorphology (ridge effect). The northern sector, where the cathedral is located, is characterized by high thickness of sandy-conglomerate deposits, but few damaged buildings are there; in this case the geomorphological factor plays an important role because here the ridge is wider, thus reducing possible seismic amplifications. Finally, the Guevara tower's sector is morphologically characterized by a long and narrow ridge and high seismic damage level, with the lowest thickness of sandy-conglomerate deposit; here the geomorphological factor is determinant in amplifying seismic intensity.

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## **Preliminary activities aimed to cluster EU cities by a geological point of view: The Urban Geo Footprint tool**

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This century is the “century of the cities”, where rapid urbanization and greater global connection present unprecedented urban challenges and concentrates risk in urban areas making them increasingly vulnerable (Coaffee & Lee, 2016). The need arises for urban planning must be asked to fully incorporate an understanding of the sub-surface into the deliberation/decision-making process (Howard, 1997).

The Urban Geo Footprint (UGF) is classification tool being developed by a sub-group of the Urban Geology Expert Group of EuroGeoSurvey (UGEG) and it is based on a multidisciplinary effort in which different skills and expertise come into play.

The main objective of this project is to set up a classification method to identify the main geological and anthropic features that influence city’s resilience related to its geological setting. A tool is being developed in order to clustering cities according to their geological and climatic features and to understand why target urban contexts have different issues (e.g. climate change, floods), and thus to assess the cities’ geo-resilience.

The UGF will help cities to understand what ‘economic’ and ‘social well-being’ benefits (i.e. in terms of ‘geological resilience’) could derive from urban planning associated with subsoil knowledge. The salient features required for this tool are: - It must be user-friendly and easy to use by scientists and non-scientists - It must be available at European level (and maybe, once is tested in Europe, it could be extended worldwide). The following main 5 drivers are defined in the tool: Geology, Climate, Geohazards, Geomorphology, Subsoil anthropic pressure. The assessment method of UGF tool will consist in testing it with data of different EU pilot-cities. The work in progress is developing a complex worksheet (which can be defined as the UGF framework ) with several quantitative parameters related to the 5 drivers mentioned above. All these parameters are going to be indexed (using scores) and weighted based on two levels of investigation: “basic” and “advanced”. The final result for each city is a general UGF score that will be the combination of all the drivers specific scores. Each tested city will be classified also by the weight of each driver in the calculation. Other objectives of the project are: - Contributing to develop a method for the comparison of data from different cities and update all existing database. - Improving the European collaboration and, therefore, the exchange of ideas on good practices to increase cities’ resilience. - Improving citizens’ awareness of both the resources and the threats associated with geology.

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## **Peri-urban geomorphology in Western Patraikos Gulf area associated with Peiros River evolution (NW Peloponnese, Hellas)**

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*Keywords:* Peri-urban geomorphology, Anthropogenic landforms, Anthropogenic morphogenesis, Geo-hydrological hazards, Human Impact, Peiros River, Peloponnese, Hellas.

Riverbed morphological dynamics are the result of the complex interaction between natural and human factors, at both local and regional scale. The study of these dynamics is essential to better understand the mechanisms that rule the functioning of fluvial systems, allowing predictions of their future evolution to be made and appropriate management measures to be taken, remediating the risks related to them.

This work presents the geomorphological features related to the anthropogenic morphogenesis of the Peiros River catchment, NW Peloponnese, Greece, combined with the geo-hydrological hazards associated with bank retreats and floods. During Holocene, human groups almost continuously occupied the area. The archaeological finds consist of pottery and other traces of human activity (temples, baths, houses, etc.) that date from the Early Helladic to the Late Roman period (c. 3000 BC- 600 AD). The material was discovered over the floodplain superficially or at depths ranging from 1.5 to 3.2 m. The deepest buried finds were found under alluvial sediments, indicating that some floods potentially tied to paleoenvironmental and climatic variations occurred in the area.

The study revealed that restriction of fluvial sediment supply, shoreline retreat, bank erosion and related riverbed migration took place over the last decade, that complies with the local tectonics of the area. The morphological changes are mainly attributed to human intervention, such as the construction of a dam and consolidation weirs that altered sediment and water fluxes. These factors combined with the climate change resulted in a dramatic alteration of the morphology in the area. These morphological changes, resulted in loss of property and boundary issues, and made the area vulnerable to flash flood events. Structures close to the coast are exposed to higher risk because of the shoreline retreat. No remediation measures have been taken so far, except for the installation of riprap of limited length and one groin, in an attempt to contrast the ongoing retreat process and reduce wave action. Other severe morphological changes were due to anthropogenic interventions related to urban sprawl and agriculture.

Thus, anthropogenic modifications of the former landscape have been particularly widespread and pervasive over the coastline, the floodplain, and the slopes. They included a general alteration of the landforms, channelization of riverbeds, and slopes terracing. The output of this research is a large-scale map, which allowed us to assess the existing relationships among structures and infrastructures, anthropogenic landforms, erosion processes and flood-prone areas. Thus, this tool provided relevant information for land-use planning and land management, in particular under the perspective of geo-hydrological hazards reduction.



## SecureGeoStreet: a semi-automatic approach of risk assessment for road network

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*Keywords:* road network, geo-hazard, exposure, risk, webGIS, toolboxes.

The present work describes SecureGeoStreet (SGS), a cyberinfrastructure entirely built in a GIS environment and accessible from many platforms such as pc, tablet, and smartphones. SGS provides a geological risk value to all segments of a road network of an area, through a semi-automated procedure.

Focused on the case study of Giarre municipality (eastern Sicily - Italy), this work is based on the calculation of several types of geo-hazard and their interaction with exposure. About geo-hazards, the analysis of geological and hydrological issues, geomorphological instability, and tectonic evidence have been performed; the identification of critical areas was done through the collection of bibliographic data from online databases, such as the IFFI project, the PAI cartography, and the Civil Protection Department database, and also through the creation of derived ancillary maps like TIN model, hillshade, slope and aspect charts.

The geo-hazard evaluation has been enriched by the interpretation of Persistent Scatterers (PSInSAR), obtained through the Rheticus® Displacement service by processing the Sentinel-1 images (from October 2014 to June 2018). The average velocity along the line-of-sight (LOS) and the displacements time-series were considered in order to identify the ground instability phenomena.

The exposure corresponds here to the vehicle flow density per road. This value was calculated starting from two models: the first one, based on a source-destination matrix, derived from a demographic map and all points of interest, weighted according to their level of attractiveness; the second one, based on Google Traffic data, takes into account the traffic variability at different times in each day of the week.

The workflow automation leads to the risk maps as well as to their web-interactive deployment, allowing at the same time, to select those road segments most susceptible to vulnerability monitoring.

The geoprocessing steps have been significantly automated creating 32 toolboxes through the use of ArcGIS Model Builder and the integration of some original Python scripts, guaranteeing the replicability in other areas and the possibility to update the risk-maps continuously over time.

Finally, the exploitation of the final risk maps has been made available online through a series of WebGIS solutions such as OGC (WMS and WFS) and KML services, cartographic previews through OpenLayers scripts, an ArcGIS Online geoportal, three Android apps, and a website with interactive maps.

SGS end-users are private companies and public administrations, which can receive immediate support for the monitoring and territorial planning phases as well as mitigate the risk in the road network.

ArcGIS - <https://www.arcgis.com>

IFFI Project - [www.progettoiffi.isprambiente.it](http://www.progettoiffi.isprambiente.it)

Italian Civil Protection Department - [www.protezionecivile.gov.it/](http://www.protezionecivile.gov.it/)

OpenLayers - <https://openlayers.org/>

P.A.I. - [www.sitr.regione.sicilia.it/pai](http://www.sitr.regione.sicilia.it/pai)

Rheticus displacement - <https://www.planetek.it/>

## **Urban geomorphology – The need to increase the links with urban planning**

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*Keywords:* urban geomorphology, geomorphological heritage, urban planning.

Urbanization is a global phenomenon and currently more than half of the world's population lives in urban areas. Studies on urban geomorphology and urban geomorphological heritage and the development of specific methods of investigation (assessment, inventories, cartography) are still relatively rare and limited (Reynard et al., 2017). This keynote talk proposes first an overview stressing the importance of geomorphology in urban issues (such as topographical constraints, sources of materials, urban heritage, etc.). Second, it shows various examples of geomorphological studies in urban contexts, and the interest of different types of methods (historical methods, fieldwork, mapping). Finally, it advocates for more links between geomorphologists and urban planners.

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## Landslides affecting buildings in rapidly growing areas of Cuenca (Ecuador)

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*Keywords:* landslide risk, buildings, vulnerability, Cuenca.

Landslides represent a serious threat in hilly and mountainous areas of the world. Usually, shallow landslides are triggered by intense or prolonged rainfalls and frequently may evolve into potentially catastrophic flow-like movements. Because of the capacity of these phenomena to travel long distances, buildings and infrastructures located in areas improperly deemed safe can be affected. Landslides can be destructive events when mobilize large volumes of soil and/or rock and undergo long distances. It is impossible to stop such events and the best way to prevent disasters is to reduce or avoid the related risk (Carrara et al., 1999).

Landslide risk assessment is a research topic of growing interest across the scientific community. Such interest stems from the awareness of the still dramatic impact of landslides on the socio-economic development of vast areas and the concurrent boosting request for urbanization across landslide-prone areas (Petley, 2012). Risk mitigation measures must necessarily focus on the vulnerability of the exposed elements and, in particular, of buildings potentially impacted by landslides. The destruction of these structures can provoke enormous economic losses and endanger the people inside them.

On this basis, a study concerning landslide impacting settlements in the Cuenca area (Ecuador) has been carried out thanks to the availability of two fundamental datasets: landslide inventory map (LIM) and information on building's presence. A LIM represents a fundamental tool to display information on landslides activity and their multi-temporal evolution (Corominas et al., 2014). In most cases, inventories are discontinuous over time and so-called event-based landslide inventories are available, which are landslide inventories based on a singular severe event (rainfall- or earthquake-induced). In this case, LIM was derived from interferometric data and the visual interpretation of aerial photos integrated and validated by field investigation. The surveyed slope failures were classified according to Cruden & Varnes (1996). As concerns buildings information, it was possible to obtain multi-temporal data on the evolution of buildings constructed from 2010 to 2020. From this knowledge, it was possible to note that over time, due to the steady population increase, most of the buildings were built in correspondence of the mountainous areas surrounding the Cuenca center. Thanks to the availability of these data, it can be stated that the buildings, over time, have been built in areas that can potentially be affected by landslides.

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## **The key role of anthropic underground cavities in the urban geology: the Etruscan Well in Perugia's upper town (Umbria, central Italy)**

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*Keywords:* urban geology, geomorphology, Etruscan Well, Perugia.

In highly urbanized contexts for millennia, the presence of underground artificial cavities represents one of the most important opportunity for the investigation of geological subsoil. Thanks to urban geology, it is in fact possible to combine the intrinsic geological aspects and characteristics of a city's underground with the man-made changes of the original natural landscape. This paper focuses on the investigation of a crucial key point for the geological and geomorphological arrangement of the Perugia's hill, the capital city of the Umbria region (central Italy). The study case is the area close to the Etruscan Well (third century B.C.), one of the most relevant archeo-geosite in the downtown of the city. Through a multidisciplinary approach moving from a geological and geomorphological data to historical-archaeological ones (Melelli & Rosati, 2019) with information of the hydraulic works of Perugia (Bergamini, 1991), it has been possible to rebuild the architecture of the anthropic cavities and to establish the possible connection with this ancient hydraulic works, in relation to the geological and geomorphological structure of the area. In addition, non-invasive geomatics investigations such as terrestrial laser scanner (TLS) and ground penetrating radar (GPR) have been used. The GPR survey, successful already use in historical urban areas (Ercoli et al., 2016), was planned on the data formerly obtained by the georeferenced TLS survey. The result is a three-dimension visualization of the Etruscan Well and the surrounding area, enriched by the numerous subsoil profile collected. The elaboration of these profiles and their subsequent study have allowed to expand the knowledge on an area as old as it is still unknown: focused on the interpretation of the anomalies found in the subsoil, revealed other artefacts around the Well, such as buried tunnels or possible fragments of ancient roads (Melelli et al., 2021).

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## **Geomorphological hazard and environmental impact along the urban coastal strip of Camogli city (Liguria, Italy)**

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*Keywords:* cliff, landslides, geo-hydrological hazards, tourism.

The town of Camogli is known for its beauty as tourist place, famous for its small fishing harbour and for coastal seaside residences. Despite its prehistoric origins, the urban core developed only from the medieval period. Camogli is located in the eastern part of the Golfo Paradiso, about 20 km E of Genoa, very close to the Portofino Promontory (Ligurian, Italy): the centre is entirely built on a rocky coastal cliff with an average NW-SE orientation. The cliff, frequently exposed to the Libeccio wind and SW wave, is constituted of marly-limestone and shales layers characterized by a complex geological and tectonic structure. This place is the quintessential of mediterranean high coast and in particular of the ligurian one, as it is densely urbanized and affected by rock erosion and rock fallings that expose important cultural and landscape elements to a high geo-hydrological risk. We analyzed the geological and geomorphological urban features of Camogli, and we recognized and described the cliff evolution by comparing the past morphology with the current one, focusing on the internationally-known cliff-top cemetery collapse occurred on 23 February 2021. Historical-geographical, field survey, and remote sensing data were considered. Counterintuitively, the results showed that in the cemetery area, specifically the Camogli western sector between Cala dei Genovesi and the harbour, limited anthropogenic modifications corresponded to an evident instability with a high geo-hydrological hazard associated to rock mass that led to the recent disaster in the cemetery. On the contrary, in the eastern urbanized sector (historical center), where the cliff is barely recognizable and protected by the harbour and the artificial beach constituted of the Genoa-Pisa railway line fillings, geo-hydrological hazard is lower. The cliff retreat rate, assessed for the last 110 years through experimental topographic surveys and detailed historical maps, appears in compliance with the values recorded in other Mediterranean and worldwide coastal areas presenting cliffs with similar geological and geomorphological characteristics.

## **Identification computation and mapping of anthropic landforms in urban areas: case studies in the historical centre of Genoa (Unesco World Heritage)**

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*Keywords:* old cities, photogrammetric analysis, old maps, georeferencing, contour lines.

In recent years, there has been growing interest in urban geomorphology both for its applications in terms of landscape planning, and its historical, cultural and scientific interest. Geological and geomorphological surveying in these environments, however, is complicated, as historical cities went through several phases of urban stratification and expansion. Landscape modifications became particularly significant between the second half of the nineteenth and the second half of the twentieth century, a period identified as the possible start of the Anthropocene. Anthropogenic modifications are classified as filling, excavation and mixed landforms, at different scales: unlike natural features, whose survey in the field is usually sufficient to identify the process and related landform, anthropic landforms require detailed field surveys, the comparison of views, photographs and maps, and geognostic investigations.

This research presents the results of a multi-temporal methodology applied to the historical centre of Genoa where information from nineteenth-century maps were overlaid on remote sensing data. The results have been tested by direct observations and by the analysis of stratigraphy from the regional geognostic database, updated by Genoa Municipality. In particular, drawings and paintings from the eighteenth/nineteenth century and historical photographs represent parts of the city that were heavily modified in recent times, allowing digital perspective techniques and photogrammetric analysis to reconstruct elevations and volumes. A map from Ignazio Porro (first half of the nineteenth century) has been digitalised and its contour lines and elevations rendered on a 1:2.000 scale map and compared with high resolution Lidar images from 2018; in addition, other historical maps were analysed, including the “Minute di Campagna” produced by the Sardinian Army in the early nineteenth century and nautical maps from Istituto Idrografico della Marina Militare. Through the use of GIS, the methodology was applied to three significant case studies: the area of Piazza Dante and Piazza De Ferrari; Circonvallazione a Mare road and Mura della Marina; the Acquasola area. Map overlay allowed the identification of anthropic landforms, their mapping and volume quantification. Based on the results of this analysis, we argue that the same methodology can be applied to other historical urban contexts.

## The hidden rivers of Naples (southern Italy)

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Keywords: river network, volcanic landform, anthropic loading, Campi Flegrei.

The town of Naples is located in the eastern sector of the Campi Flegrei, a volcanic field placed along the Tyrrhenian flank of the southern Apennines. The geological evolution of Naples is strictly related with the volcanic history of the Campi Flegrei (Ascione et al., 2020, and reference therein). The present-day topography results from the interaction between volcanism, bradyseism and sea-level variations and is prone to the development of a dense network of ephemeral rivers, some of which develop along faults and fractures affecting the volcanic units (Ruello, 2008).

According to the features of river networks, the town of Naples may be sub-divided in three sectors. To the west of Naples (e.g., near Agnano, Pianura, Soccavo, Fuorigrotta, Bagnoli, Posillipo and Chiaia), river network consists of small, often isolated, valleys (length around 1 km), dissecting both the inner and outer flanks of the Campi Flegrei caldera (whose slope also exceeds 30°). In the central sector of Naples (e.g., near Vomero, Camaldoli, Capodimonte and the historical centre), river network is more organised, with “small” valleys converging towards “large” valleys. Consequently, large drainage basins may be recognised, which collect water from the hilly areas towards the low topography, very densely urbanised, historical centre. To the east of Naples (e.g., near Poggioreale, Ponticelli, San Giovanni a Teduccio), river network consists of a main trunk, the Sebeto River, flowing in the related alluvial plain.

Most of the river network is very hard to be recognised, being overwhelmed by the growth of the town. A typical example is the Sebeto River, which actually flows below ground level and whose mouth has been included in the harbour area. The lack of river valleys is apparently in contrast with the alluvial events that struck Naples since historical times, as testified by alluvial deposits found in the subsurface (Cinque et al., 2011; Romano et al., 2013). Some of these events are pretty “famous”, such as those one that often hit the quarter named Sanità, which are known as the “Lava dei Vergini” due to volcanic clasts transported during the alluvial event.

Noteworthy, the memory of “hidden” rivers remains in the name of many streets, as testified by the terms “Cupa”, “Cavone”, “Vallone” and “Arena” that identified sectors of the urban areas developed on river valleys. These features make Naples an interesting study area to analyse the interaction between natural processes and anthropic loading, and to make people aware of landscape dynamics.

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## Geomorphological classification of the landscape in urban areas: anthropogenic landforms in Genoa, Rome and Perugia

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*Keywords:* urban environment, geomorphology, mapping, Genoa, Perugia, Rome.

Research in urban geomorphology is a relatively recent topic and its theory and practice require continuous updates. Few studies have focussed on issues specifically connected with the cartographic representation of geomorphological processes and landforms in urban environments, with the aim of tentatively reconstruct and clarify the original physical landscape. Among these, recent urban geomorphological surveys conducted in Italian cities proposed new strategies for detecting and mapping human induced modifications to the topography, and anthropogenic landform classification has been recently deepened in the revised Italian national guidelines for geomorphological mapping (Campobasso et al., 2018), proposed by the Working Groups of the Italian Association of Physical Geography and Geomorphology (AIGeo) and the Italian Institute for the Environmental Protection and Research (ISPRA).

In this work, natural landforms modified by man and artificial landforms are explored and compared in three Italian cities: Rome, Genoa and Perugia. The comparison is interesting because of the different morphogenetic environment characterizing the 3 cities and also for the differences in the geomorphological survey and mapping. At the same time, in these urban areas, human activities have similarly remodelled the topographic surface and become the most important modelling agent of relief. Many reliefs have been erased, whereas thick layers of anthropogenic deposits covered most of the natural landforms, with the result, for example, of hiding or greatly modifying the natural valley incisions.

Geomorphological studies in urban environments allow the reconstruction of the physical landscape before human modifications and the implementation of innovative methodological tools, and an effective legend to represent the urban landforms and their evolution over time.

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## Study of periodic dependencies among ground deformation, rainfall and sea level in the city of Naples (Italy)

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*Keywords:* interferometric data, rainfall, sea level, time series analysis, Naples.

Since early 1990s, the advent of satellite-based techniques, such as the Differential Interferometry Synthetic Aperture (DInSAR) (e.g. Curlander & McDonough, 1991) and Global Navigation Satellite System (GNSS), has revolutionized the monitoring of ground level displacements thanks to satellite-based techniques. These observation systems enabled us to control with unprecedented accuracy and resolution deformation phenomena caused by transient events, such as earthquakes, volcanic eruptions and sinkholes, or long-term processes, like subsidence and landslides, thus revealing useful applications in the geological, geotechnical and structural analysis fields (e.g. Lanari et al., 1998; Herrera et al., 2009). Today, the Advanced DInSAR (A-DInSAR) technique is based on high resolution sensors, which monitor the evolution of instability phenomena in any atmospheric and lighting condition, and in both historical centers and archaeological sites. Within this framework, we propose the application of an exhaustive approach for studying both permanent and periodic components of vertical land deformation in the urban area of Naples (southern Italy). Such methodology, successfully applied in the Po Delta area (Vitagliano et al., 2020), is proposed to study the geological risks in urban areas and to evaluate the effects of the anthropic context on the periodic processes related to climate variability. Firstly, a spatial analysis has been carried out to calculate the interferometric velocities of Sentinel-1 and COSMO-SkyMed data in the time intervals January 2016 – December 2019 and March 2017 – December 2020, respectively. The obtained ground displacement and velocity have been used for mapping the stable and unstable urban areas and for evaluating the dependencies between the distribution of the velocity zones and some geological features (e.g. ancient alluvial deposits and paleo-coast lines). Afterwards, a spatial-temporal analysis of continuous GPS data available for a site located in the city center has been performed, which provided a reliable identification of the seasonal trends of the ground displacement. Finally, an automatic cross-correlation procedure developed in Matlab environment was applied to systematically correlate the interferometric trends of each reflection point with the rainfall and sea level oscillations, measured in the same time interval. The correlation process allowed the identification of the most significant dependencies and the triggering mechanisms of the slow soil oscillations, and gave also interesting insights into urban instability processes, such as sinkholes.

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## Urban areas and geological and geomorphological setting in Central Italy

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*Keywords:* urban geomorphology, geomorphology, Central Italy.

Despite the variety of cultural approaches, delineating the geographical boundaries of urban areas is a complex task. The simplest solution is using administrative boundaries instead of using criteria based on presence/absence of population, or of alternative proxies of human presence. Administrative boundaries, though, do not necessarily represent human presence, nor geomorphological settings.

This work analyzes the urban boundaries, proposed by Alvioli (2020) for the whole of Italy, with the geological and geomorphological features in Umbria, Central Italy. Urban areas – namely, “natural cities” – were delineated with a parameter-free method based the head/tail breaks of areas related to human mobility, using open data for settlements and road networks. Umbria is an excellent example of the geomorphological evolution resulting from the compressive and successive tectonic phases occurred in central Italy, showing a strong correlation between human settlements and morphological setting (Della Seta et al., 2017).

We found that the factors showing the most relevant correlations with urban areas are the geological and geomorphological settings. A weighted spatial analysis in GIS, and comparison of the geological and geomorphological features with existing urban areas, identified “geomorphological corridors” as promising geographical areas for development of mobility infrastructures.

In addition, the resulting areas may be analyzed considering both natural risks and natural resources. The susceptibility to earthquake, flooding and landslide events may be measured as well as areas characterized by a high value of geoheritage resources. These negative and positive characteristics of a geographic area can decrease or increase their attitude to human presence. Therefore, the geomorphological units can suggest not only the best location and the best position for new urban areas but also the landscape management for a sustainable and environmentally friendly future. In the post-Covid19 era, finding new ways of living beyond urban sprawl seems a mandatory task, and the approach presented here may relevant to single out new areas for urban development.

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Della Seta M., Melelli L. & Pambianchi G. (2017) - Relief, intermontane basins and civilization in the Umbria-Marche Apennines: origin and life by geological consent. In *Landscapes and Landforms of Italy* (pp. 317-326). Springer, Cham.

## **The role of urban geology and geomorphology in the prevention and management of natural risks: the example of the town of Camerino**

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*Keywords:* natural hazards, urban geomorphology, 2016 central Italy earthquake, urban planning.

Following the seismic sequence that affected central Italy starting from 24 August 2016, the historic center of Camerino was completely abandoned due to the high number of unusable or partially collapsed buildings. The possibility of operating in an area that is still partially accessible and with ongoing investigations for the planning of the reconstruction phase made it possible to find new stratigraphic data, carry out deep geophysical prospecting and, in general, carry out detailed surveys. The collected data, integrated with previous studies and historical-archaeological information, have highlighted the presence of both natural and anthropogenic anomalies within the bedrock that have notably conditioned the evolution over time of the historic center. These new data make it now possible to define with greater precision the geological setting of bedrock and the main active geomorphological processes, providing at the same time useful indications for the planning and implementation of the restoration/reconstruction interventions of the buildings and the definition of the natural risks present.

## **The district of San Giacomo dei Militari: reconstruction of the subsoil of the most ancient area of the Palermo City (Italy)**

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*Keywords:* urban geomorphology, archaeological features, geophysical surveys.

The urban zone of Palermo includes a central core formed by the historic center, one of the largest in Europe. The town's urban development has led to changes in the topography and the growth of civil engineering structures covering rocks, deposits, and natural landforms. In this area, a geomorphological map describes the geomorphological evolution from Quaternary to Anthropocene (Cappadonia et al., 2019). To better support urban planning, a more precise study phase is underway to define the areas affected by local developments across the time. The district of San Giacomo dei Militari rises in the heart of the city in the highest part of the promontory between the Kemonia and Papireto rivers. This part of the city corresponds to the Paleopoli, a city center dating back to the Punic age. During the Arab-Norman period, the district was called with the Arabic term Galka (the fence). It included the royal palace, the Curia palace, and the military quarter, surrounded by walls and high towers.

The geological data of some boreholes were integrated with the results of geophysical seismic surveys to reconstruct a geological and geomorphological section of the ancient district of San Giacomo. In particular, HVSR seismic data (Nakamura, 1989; 2000) were acquired, the inversion of which was constrained by the values of the shear wave velocity obtained from a MASW survey (Park et al., 1999). In addition, a seismic refraction tomography was performed at the royal palace.

The reconstruction of the subsoil in this area of the city cannot ignore historical and archaeological reconstructions. In this part of the ancient inhabited nucleus, the buried walkways were excavated directly into the calcarenite and placed above the ancient piezometric level. A detailed geological section was carried out in this area which, together with the other data, will also constitute a useful tool for defining the criticalities in the area related to the presence of cavities (anthropogenic/natural) and the cultural heritage resources.

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Nakamura Y. (1989) - A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quart. Rep. Railway Tech. Res. Inst. (RTRI)*, 30, 25-33.

Nakamura Y. (2000) - Clear identification of fundamental idea of Nakamura's technique and its applications. In: *Proc. 12th World Conf. on Earthq. Eng.*, New Zealand.

## The geology and geomorphology of the city of Venice and possible site effects related to the 1117 earthquake

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*Keywords:* fluvial incised valley, lagoon, co-seismic sand liquefaction, seismic hazard, sea level change, geoarchaeology.

The area of Venice was subject to a complex sedimentary and geomorphic evolution. In the Last Glacial Maximum (LGM), it was part of the alluvial megafan of the Brenta R., that experienced a major aggradation phase between ca. 27 and 17.5 ka cal BP (Rossato & Mozzi, 2016), followed by the cutting and filling of fluvial incised valleys in the Late Glacial and early Holocene (Mozzi et al., 2013). The lagoon, whose sediments lie on the pedogenized interfluvial and the incised valley fills, started forming at ca. 7 ka cal BP.

We reconstruct the detailed stratigraphy of Venice underground down to ca. 20 m depth, through the analysis of about 500 cores and 130 penetrometer tests. Results show two main post-LGM fluvial incised valleys infilled by well-sorted sand that run approximately west-east under the city. We further analyze the geoarchaeological record from archaeological excavations, for recovering the elevation in respect to the relative sea level of ancient trampling levels since the early Middle Ages.

Results indicate that, in a general framework of increasing relative sea level, differential ground-surface lowering up to 1 m occurred before the 12<sup>th</sup> century AD in the archaeological sites located above the well-sorted fluvial sands of the incised valleys. The chronology of the displaced archaeological levels and the geotechnical characteristics of the underlying sediments rise the question of a cause-effect theory to interpret the sinking of building structures as possibly caused, at least partially, by seismic sand liquefaction during the major January 3, 1117 earthquake. This is the highest known seismic event that ever hit the region, with Mw 6.8 to 7 and epicenter near Verona, about 90 km west of Venice.

In order to check this hypothesis, we compared the cyclic stress induced by this earthquake with the cyclic resistance of the sandy deposits against liquefaction. Cyclic stress is estimated from the expected ground acceleration in Venice in respect to magnitude, distance and attenuation by the specific sedimentary succession for the 1117 earthquake. The cyclic resistance is estimated from cone penetration tests (Robertson 2010). Results seem to support the possible occurrence of co-seismic sand liquefaction in the sandy infilling of the buried fluvial incised valleys of Venice.

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Robertson P.K. (2010) - Evaluation of flow liquefaction and liquefied strength using the cone penetration test. *J. of Geotechnical and Geoenviron. Engineer.*, 136, 842-53.

Rossato S. & Mozzi P. (2016) - Inferring LGM sedimentary and climatic changes in the southern Eastern Alps foreland through the analysis of a 14C ages database (Brenta megafan, Italy). *Quaternary Science Reviews*, 148, 115-127.

## Geological-geomorphological conditioning on the development of historical centers: the example of Gubbio (Umbria, central Italy)

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*Keywords:* urban geomorphology, historical centers, urban development.

Gubbio (Umbria, central Italy) was built on the slope of Mt. Ingino (908 m asl), on the left bank of Torrente Camignano, where the vast flat area known as the “Gubbio Plain” begins.

The debris at the base of the slope of Mt. Ingino is delimited by two alluvial fans, one of the Torrente Camignano at NW (almost flat) and the other of the Fosso Cavarello at SE (more steep). The slope debris shows an evident morphological step (H max. about 20 meters) oriented parallel to the slope itself. This produces a marked discontinuity in the slope profile and affects the whole width of the detrital body.

This kind of escarpments is frequent on the slope debris at the base of the mountains of the Gubbio chain. This ridge constitutes the NE flank of an anticline, formed during the Apennine orogeny. It is broken at the core by a normal fault with considerable upthrow (over 1500 meters) and with direction parallel to the axis of the fold itself. These escarpments are likely to be interpreted as the surface morphological expression of recent phases of tectonic activity linked to the Gubbio fault (which, therefore, has to be considered an active and capable fault).

A bull of Pope Clement III in 20 October 1188 and a diploma of Emperor Henry VI in 5 June 1191 suggest that when the Eugubini (the people of Gubbio), in the second half of the 12th century, decided to build the new city “on the mountain”, they identified how the most suitable place for the fortified urban space, the one upstream of the great escarpment which divided in two parts the slope debris of Mt. Ingino.

Later, especially during the 13th century, a consistent urbanization took place in Gubbio. This led to an inevitable expansion downstream of the urban core, which essentially took the shape of the current historic center of the city.

On the specific topic of the relationship between the definition and development of the late medieval city of Gubbio and the conformation of the slope debris on which it was built, some preliminary considerations have already been formulated (Sannipoli, 2013).

The research in progress is aimed at investigating some specific aspects of this interesting problem of urban geomorphology, both as regards a more precise definition of the geomorphological characteristics of the site, and in relation to the transformations of the first urban core of Gubbio, over the 13th and 14th centuries.

Above all, it seems interesting to define what these transformations entailed, as regards the alterations of the geomorphological peculiarities of the site where the city was born and had subsequently developed.

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## **S26. Geo-heritage, geoparks, geo-itineraries**

*CONVENERS AND CHAIRPERSONS*

*Piero Gianolla (University of Ferrara)*

*Cristina Giovagnoli [ISPRA]*

*Matevž Novak [Geological Survey of Slovenia]*

*Alfio Viganò [Servizio Geologico - Trento]*

## **Integrating airborne laser scanning and full 3-D Ground Penetrating Radar for the investigation of protohistoric structures in Croatian Istria**

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*Keywords:* Airborne Laser Scanning, 3-D Ground Penetrating Radar, protohistoric structures, Croatian Istria.

The integration of cutting-edge non-destructive photogrammetric, remote sensing and geophysical techniques is dramatically changing the investigation of archaeological sites, providing crucial information about topography, geometry and spatial relationships among cultural heritage and other natural or anthropogenic features. We applied an integration of Airborne Laser Scan (ALS) and full 3-D Ground Penetrating Radar (3-D GPR) to study two protohistoric sites located in the surroundings of Oprtalj/Portole (Croatian Istria). The study was carried out in the framework of a multidisciplinary project that aims at understanding the diachronic development of the archaeological landscape of a strategic sector of the Istrian peninsula.

The acquisition, processing and analysis of high-definition ALS data combined with the examination of aerial pictures, historical cadastral maps and repeated surface surveys allowed a detailed archaeological mapping of the area. The investigations carried out over about 30 km<sup>2</sup> allowed to identify and describe several unreported prehistoric, protohistoric and Roman sites, to obtain detailed topographic information about the already known ones and to recognize different settlement forms and occupation strategies related to cultural and/or environmental factors (Bernardini & Vinci, 2020).

The selection of a probable protohistoric burial mound and a small protohistoric hill fort for full 3-D GPR survey was motivated by the presence of surface archaeological finds, the limited size of detected structures, the absence of dense vegetation and the suitability of these features for future excavations.

The analysis of GPR data collected at both sites and integrated with ALS allowed to image in detail the morphology of the structures and associated earth deposits, providing additional and relevant information for the interpretation of both complexes. From a methodological point of view, the obtained results proved the effectiveness of integrating different non-destructive techniques applied to field archaeology.

Bernardini F. & Vinci G. (2020) - Archaeological landscape in central northern Istria (Croatia) revealed by airborne LiDAR: from prehistoric sites to Roman centuriation. *Archaeological and Anthropological Sciences* 12. <https://doi.org/10.1007/s12520-020-01070-w>.

## East Vardar Ophiolite from North Macedonia revised within the GECCOSPARK know-how exchange programme (KEP) project funded by the Central European Initiative (CEI)

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**Keywords:** East Vardar Ophiolite, North Macedonia, Geccosparks, Geoparks, volcanic arc, back-arc basin.

This contribution is part of a CEI-KEP project (Ref. No. 1206.006-19) titled “*Promoting geological, ecological and cultural heritage through sustainable development and creation of geo-parks*”. It includes the study of Mesozoic ophiolite rocks, which are interpreted as the remnants of the Vardar Tethys Ocean. The East Vardar ophiolites are composed of basic magmatic sequences (pillow basalts, sheeted dykes, and gabbros), associated with intermediate and acid magmatic intrusions having subduction-related affinity and locally bearing an adakitic signature (Božović et al., 2013; Boev et al., 2018). To give new insights on these ophiolites, new samples were collected from the Lipkovo and Demir Kapija localities, in the northern and southern part of North Macedonia, respectively.

Three groups of rocks are distinguished on the basis of whole-rock major and trace element composition and major element composition of clinopyroxene. Group 1 is characterized by tholeiitic basalts from Demir Kapija that exhibit slight enrichments in light-Rare Earth Element (L-REE) and slight negative Nb anomaly. These features are comparable with those of back-arc basin basalts. Groups 2 and 3 are represented by calc-alkaline rocks, showing typical subduction-related chemical affinity, as exemplified by N-MORB normalized spider diagrams showing typical Nb and Ta and, locally, P and Ti, negative anomalies along with Th-U positive anomalies. Group 2 rocks, which are from Demir Kapija, exhibit a weak adakitic affinity, as they are characterized by high LREE/HREE fractionation, high Sr/Y and La/Yb ratios.

Additional insights were provided by  $\delta^{13}\text{C}$  and  $\delta^{34}\text{S}$  analyses. Group 2 and 3 rocks show more pronounced negative  $\delta^{13}\text{C}$  (-22‰ to -18‰) and positive  $\delta^{34}\text{S}$  (+2.3‰ to +4.9‰) values compared to those of Group 1 rocks ( $\delta^{13}\text{C}$ : -16‰ to -10‰;  $\delta^{34}\text{S}$ : +0.7‰ to +2.4‰), suggesting that Group 2 and 3 rocks record comparatively higher metasomatic interaction of their mantle sources with slab-derived components.

On the whole, the results show that magmatic rocks from ophiolites of East Vardar in the North Macedonia display a widespread supra-subduction chemical signature, indicating the formation of these ophiolites in an arc - back-arc ensialic setting. The data provide information about the geological evolution and setting of this area, which should be disseminated using a didactic approach and simple concepts appealing for “non-experts”, emphasizing that such studies are crucial to understand a unique geological system, which has no analogues in the present.

Boev B., Cvetković V., Prelević D., Šarić K. & Boev I. (2018) - East Vardar ophiolites revisited: a brief synthesis of geology and geochemical data. Contributions, Sec. Nat. Math. Biotech. Sci., MASA, 39, 51-68.

Božović M., Prelević D., Romer R.L., Barth M., van den Bogaard P. & Boev B. (2013) - The Demir Kapja Ophiolite, Macedonia (FYROM): a snapshot of subduction initiation within a back-arc. J. Pet., 54, 1427-1453.

## **New geochemical data on ultrapotassic volcanic rocks from North Macedonia: revised within the GECCOSPARK know-how exchange programme (KEP) project funded by the Central European Initiative (CEI)**

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**Keywords:** ultrapotassic rocks, orogenic volcanism, North Macedonia, Geccosparks, geoparks.

Geoparks are geographical areas of international geological significance, which are managed with the concept of protection, education and sustainable development. Through the CEI Know-How Exchange Program project (Ref. No. 1206.006-19) titled “*Promoting geological, ecological and cultural heritage through sustainable development and creation of geo-parks*”, the University of Ferrara, NGO Gaya, and the Goce Delcev University of Štip want to valorise the remarkable geological and naturalistic heritage of North Macedonia, which deserves further characterization. One of the strengths of this country is the geodiversity of its landscape and the large variety of rocks, testifying the complex geological history of this region. In the late Paleogene–middle Miocene a volcanic arc developed as consequence of subduction processes started since Jurassic–Cretaceous. The main phase of orogenic magmatism was locally followed by scattered potassic to ultrapotassic volcanism, whose rocks, nowadays, crop out in several localities of the North Macedonia but they are limited in extension (Yanev et al., 2008). We focused the investigation on the ultrapotassic products that are representative of melting of extremely metasomatized mantle sources, plausibly related to subduction processes, collecting samples in the surroundings of Mlado Nagorichane (North Macedonia). The rocks are mainly phono-tephrites characterized by the presence of leucite, olivine, clinopyroxene, and phlogopite as phenocrysts and also plagioclase in the groundmass. They are classifiable as ultrapotassic, having K<sub>2</sub>O content generally >6 wt%, and a K<sub>2</sub>O/Na<sub>2</sub>O ratio of 1.9 to 2.8. The rocks have primitive composition as demonstrated by the high MgO (7.0-10.1 wt%), Cr (265-275 ppm) and Ni (204-298 ppm) contents, which conform with that of mantle-derived melts. The primitive normalized spider diagram of these rocks exhibits strong enrichment in Large Ion Lithophile Elements (LILE) coupled with Nb, Ta, Ti negative and Th-U positive anomalies, showing a “Roman Province type” affinity. These features suggest that the mantle sources have been modified by metasomatic events, possibly induced by recycling via subduction of continental crust components. Therefore, the studies of North Macedonia ultrapotassic rocks will contribute to i) understand the genesis of the orogenic volcanic rocks in the Balkan region and ii) investigate the potential analogies with those of other Mediterranean regions. These interpretations should be disseminated using a didactic approach for “non-experts”, emphasizing the peculiarity of these rocks that combine mantle (e.g., high MgO) and crust (e.g., K<sub>2</sub>O) fingerprints, as well the importance of their study to understand and interpret the past and actual geological systems.

Yanev Y., Boev B., Doglioni C., Innocenti F., Manetti P., Pecskey Z., Tonarini S. & D’Orazio M. (2008) - Late Miocene to Pleistocene potassic volcanism in the Republic of Macedonia. *Mineral. Petrol.*, 94, 45-60.

## **Meteoritics as a source of well-being for people with dementia: an experience in the Planetary Sciences Museum of Prato (Italy)**

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*Keywords:* Alzheimer's disease, multisensorial experiences, welfare, astromaterials.

According to the Alzheimer Association, dementia is an overall term that covers a wide range of specific medical conditions such as progressive loss of memory and other neuropsychological functions (e.g., praxis, speech). These symptoms are usually severe enough to impair a patient's daily life. Alzheimer's disease (AD) accounts for two thirds of dementia syndromes in people older than 65 years. According to the World Alzheimer Record 2020, over 50 million people are living with dementia worldwide. And this number is expected to double every 20 years, reaching 152 million cases of dementia in 2050. The Dementia in Europe Yearbook 2019 recored that in Italy there were 1.279.366 cases in 2018 (2.12% of population), which are set to increase to 1.460.570 cases in 2025 (2.44% of population) and 2.247.715 cases in 2050 (4.13% of population). It is therefore imperative for governments, policy makers, scientific and cultural institutions to be able to respond properly to the challenges that come with a rising number of people with dementia within their countries. In this context, cultural institutions as museums play a pivotal role in dementia awareness and education. They can serve as safe places in which run a variety of activities through an ethical use of their collections as encouraged by Convention on the Value of Cultural Heritage for Society (2005). However, the existing literature focuses particularly on museum-led programs involving art galleries and collections (e.g., the MoMa Alzheimer's Project). The goal of this presentation is to introduce attendees to the programs for people with dementia and their caregivers that have been developed at the Museum of Planetary Sciences (MSP) in Prato. This presentation will show the positive use of meteorite samples in multisensorial activities aiming to improve patients' and their carers' mood and self-esteem. The impact of such non-medical treatment, its incidence on lowering dementia caregivers stress levels, and the ascertain of the participants' satisfaction levels will be also provided.

Since its establishment in 2005, MSP is actively engaged in creating successful experiences for visitors with disabilities (e.g., blindness, visual impairment, autism), and is piloting at a national level diverse multisensory stimulation programs for people with dementia and their caregivers using astromaterials. For evaluation, quantitative and qualitative data were collected using the Neuropsychiatric Inventory Questionnaire (NPI-Q), the Mini-Mental State Examination (MMSE) test, and the Cornell Scale for Depression in Dementia (CSDD) interview. This presentation will also present the activities that have been performed during the Covid-19 pandemic. By assisting the patients and their caregivers, MSP provides an example of a much more comprehensive and meaningful museum therapy project, which represent a glimpse into the future of scientific museum programming.

## The Pietra Pece: mining history and production cycle

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Keywords: Pietra Pece, Geo-heritage, Sicily.

In the Ragusa area, in the carbonate rock levels known in the literature as the “Ragusa Formation”, the uppermost Irminio member presents bituminous impregnations in the Tabuna and Streppenosa localities. Rock impregnated with natural bitumen is called ‘asphaltic rock’; locally, it is also known as “Pietra Pece” (i.e. pitch stone).

Asphaltic rock was mined here either in opencast and in tunnels, as in the Tabuna and Cava Pece mines; in an early phase, the Streppenosa and Castelluccio sites were also important.

Pitch stone is characterized by excellent physical-mechanical properties and it has been used extensively over the centuries as building material: for instance, it is an ideal material for road paving and, in an industrial context, for hydrocarbon extraction. Indeed, it was at the end of the 18th century, when Dolomieu in his ‘Memoire sur les îles ponces et catalogue raisonné des produits de l’Etna’ spoke of a soft limestone, impregnated with hydrocarbons: ‘under the July sun, the black stone can be cut with a knife’, that it became known throughout Europe.

Extraction and marketing were managed at an early stage by foreign companies, and the asphalt from Sicily arrived on the roads of half of Europe: Berlin had more than a million square metres of Ragusa asphalt road surfaces; other cities worth mentioning are Paris, Amsterdam, London, Milan and Palermo.

Over the years, the extraction phases underwent inevitable evolutions and changes, oscillating between a natural preference for the use of rock as road surfacing and the extraction of bitumen itself: this latter was preferred by the first A.B.C.D., which built a battery of sixteen furnaces for the distillation of asphaltic rocks.

But if, after the Second World War, the asphalt-related industries underwent a vast and irreversible process of devaluation, since bitumen had by then supplanted by compressed asphalt in road paving, the Sicilian Region intervened by encouraging the extraction of ‘pitch stone’, typical productions and the very reconversion of the asphalt industry, which saw the birth of the second A. B.C.D., where the first A. B.C.D. was built, where the production of cement obtained from exhausted asphalt rocks from distillation was added.

It was in 1944 that A. Ancione SpA appeared on the Hyblaean market of SE Sicily: in this area, now disused, the enormous investments were done and there it is possible to investigate the production cycle divided into four large production areas: asphalt tiles, road asphalt (later replaced by bituminous conglomerates), mastic and lime.

The study punctually analyses the first three of these sectors, which are intimately linked to C.da Tabuna quarry district and to pitchstone marketing. Finally, it is worth noting that the Tabuna-Streppenosa site has been proposed for the establishment of a Geosite of national importance pursuant to L. R. 25/2012 and with D. A. 238/2018 it has been included in the list of sites of geological interest of the Sicily Region.

## **The UNESCO Aspromonte Geopark: the Migrant Lands Geopark, where the Footsteps of the Water and the Greeks of Calabria meet the Spirituality of Stones, between “Asper”-Mountain and “Asper”-Sea**

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*Keywords:* Aspromonte Geoparks, Crystalline basements, Calabria-Peloritani Orogen.

The Aspromonte Massif represents the southern edge of the Italian peninsula in geographical continuity with the Apennine chain from which differs for the occurrence of crystalline-metamorphic rocks. These last are locally covered by several peaks and various plateaus of sedimentary origin. The constant and still active uplift makes the Aspromonte Massif one of the most geologically active areas in the Mediterranean realm, with the consequent formation of steep landscapes, gorges and almost inextricable ravines that climb in a short distance from the sea up to 2000 meters.

After a long and complex procedural process carried out by a special committee of scientists and local associations coordinated by the Aspromonte National Park, on 22 April 2021, the Aspromonte was recognized by UNESCO as “Aspromonte Geopark” and became part of the UNESCO GLOBAL GEOPARKS Network.

The Aspromonte geopark “system” is a natural laboratory for the observation of the very slow to very fast tectonic movements of the Earth system, as well as for its ecosystem interrelations. This implies a high scientific research interest and an experiential knowledge site useful for educational and geotourist purposes. In the Aspromonte Geopark, the geological footprint on the landscape is so strong and well recognizable that it has a decisive impact on other processes of natural and anthropogenic transformation.

Essential components of the GeoSystem are: crystalline-metamorphic rocks and mylonites; the sequence of marine and continental terraces; the alluvial planes made by the “Fiumare” erosion, the valley of the “Grandi Pietre” with its arenaceous Monoliths, the “dolomitic” landscape with pinnacles and spiers, several waterfalls and gorges; the very large landslides locally linked with deep gravitational deformations of the slopes. All of these variegated geological landscapes have carried out to the institutions of 89 geosites within the Geopark perimeter, 8 of which recognized as international significance.

The Aspromonte can be then defined as a real “Earthgate” on the past, present, and future of the Earth. Crossing it means, opening one’s look to remote geological times and distant places on the Earth, which bring to mind continents, seas, and oceans that today no longer exist. Clutching in the hand a fragment of its singular crystalline-metamorphic rocks - which date back to over 500 million years ago - so different in nature and appearance to the sedimentary sequences of the Apennines - one feels, in some way, united to the geological history of the European Hercynian massifs, since the Aspromonte shares a good part of their history.



### **Three-dimensional geological cartography for geotourism: the Regional Reserve of Montalbano Jonico**

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*Keywords:* 3D geological cartography, geotourism, geoitineraries, badlands.

The combination of new technologies in data collection, storage, modelling and visualization has recently provided the tools to turn 2D geologic mapping into 3D, which is useful to optimize information, facilitating immediate understanding of geologic architecture even for non-experts. In this perspective, with the aim to promote also geotourism in the Regional Reserve of Montalbano Jonico Badlands (MT, Italy), we are implementing a 3D geological map, from a 2D geological map, at 1:5.000 scale. The Quaternary marine clayey hillslopes of the Reserve belong to the inner margin of the Bradanic Through and show typical landforms giving rise to a stunning badland landscape. These forms derive from erosion, due to water washout, in clay-rich lithologies slopes, characterized by a high drainage density, scarce vegetation cover and high energy relief. In the past thirty years, several studies allowed to highlight, exposed in the badlands of the Reserve, one of the best representative marine sedimentary section outcropping on the Earth, offering the opportunity to study and analyze in detail the stratigraphical constraints close to the Lower – Middle Pleistocene boundary and the paleoclimatic evolution during the Marine Isotope Stage 19 interglacial stage (e.g. Marino et al., 2020, and references therein). The 3D geological model was built using the software Move, a powerful platform that allowed to combine a DEM 5x5m resolution, 2D large scale geological map, field data acquired with mobile/tablet and any kind of survey data, as geologic cross-sections and wells logs. The use of three-dimensional cartography makes much easier to visualise how the proposed geo-itinerary develops between the geological and geomorphological features of the area. As a simple and diverse output, 3D cartography could help to promote a broader communication of the scientific topics and the awareness of the importance of the geological heritage of this area for cultural, educational and other local sustainable activities, sharing it with the stakeholders.

Marino M., Girone A., Gallicchio S., Herbert T., Addante M., Bazzicalupo P., Quivelli O., Bassinot F., Bertini A., Nomade S., Ciaranfi N. & Maiorano P. (2020) – Climate variability during MIS 20-18 as recorded by alkenone-SST and calcareous plankton in the Ionian Basin (central Mediterranean). *Palaeo.,Palaeo.,Palaeo.*, 560. <https://doi.org/10.1016/j.palaeo.2020.110027>.

## **The Urban Park “Tevere alla Magliana” (Rome) as a natural laboratory for the teaching and dissemination of Natural Sciences in the context of the Agenda2030 for Sustainable Development**

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*Keywords:* urban public parks, sustainability, scientific dissemination.

The “Tevere alla Magliana” urban Park extends for one kilometre in the floodplain area on the right bank of the river, upstream of Ponte della Magliana, behind an area of recent and heavy urbanization, identified as a marginal area of Rome. Here a well-managed green space, inaugurated in 2014, that still keeps the signature of the natural environment, represents a laboratory for cultural and naturalistic exploration that can greatly benefit the wellbeing of the citizens of the district and the city. In spring 2021, Roma Tre University students attending the Course “Agenda 2030 for sustainable development for Life and Earth Sciences” developed in the Park their practical stage to study specific features of this natural environment in the urban context such as the endemic vs exotic plant distribution, the rocks from Latium used for urban decoration (statues, fountain, etc.), the river dynamics, the effectiveness of a phytodepurative system, underlying the area resources and vulnerabilities. The scientific contents were then synthetised and simplified for Natural Science dissemination with reference to some of the Goals of the Agenda 2030. The presentation will illustrate the steps and outcomes of this teaching and dissemination experience.

## The overturned succession of “La Rocca” (Roccapalumba): an historical geosite for the pelagic Jurassic of Sicily

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*Keywords:* Jurassic, Sicily, ammonites, stratigraphy, geosites.

Roccapalumba is a large calcareous block close to the homonymous village located in central-western Sicily between the Madonie and the Sicani Mountains. The calcareous block represents a prominent morphological feature of this locality that has been investigated since the end of 1800 for the paleontological record, namely the ammonites.

The Roccapalumba block exposes an overturned Mesozoic pelagic succession that overthrust clastic deposits of Neogene age. The lower part of the pelagic succession, Middle to Upper Jurassic in age, is exposed along an abandoned quarry. It mostly consists of about 70 m of well-bedded brown to reddish calcilutites, passing down-section to Calpionellid limestones of uppermost Jurassic-lowermost Cretaceous age and, in turn, to ca. 20 m of Upper Cretaceous Scaglia-type calcilutites. Owing to the overturned position, the lowermost stratigraphical levels, ranging in age from late Bajocian to Bathonian are located on top of “La Rocca” (Meléndez et al., 2010), whilst the Cretaceous calcilutites occur at its base as confirmed by recent sedimentologic and biostratigraphic studies. Only a few ammonites, among the specimens recognized, have been collected and are kept at the G.G. Gemmellaro Museum. Most of them were left in situ because they constitute tangible evidence of the reversal of the stratigraphic order.

Another interesting limestone block crops out, about 3 km Est from Roccapalumba, along the River Torto, known as Rocche Fiaccati. This outcrop was investigated by G.G. Gemmellaro who published a paper in 1874 describing new Oxfordian taxa and a large macroconch of *Euaspidoceras* genus that today are part of the Gemmellaro Museum collections.

Many archeological finds of different ages (Neolithic, Early Christian, Late Roman/Byzantine and late 15th century-mid-18th century) have been described from the Roccapalumba area (Mannino, 1998).

According to the “Protocol on geoconservation principles” (ProGeo, 2011), the important paleontological content of the Jurassic successions from the Roccapalumba area, the overturned stratigraphic position of “La Rocca”, the historical value of these sections coupled to the abundant archaeological evidences and the rich cultural traditions, make this area worth being considered as a prominent multiple geosite.

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Meléndez G., D’Arpa C., Di Stefano P., Bello J. & Ramajo J. (2010) - Callovian to lower Kimmeridgian ammonite successions from West Sicily (Roccapalumba) and Northeast Iberian Range (Ariño, Teruel): A key for palaeogeographical reconstruction. Volume del “V Congreso de Jurásico de EspañaClave”, 103-111.

ProGEO (2011) - Conserving our shared geoheritage - a protocol on geoconservation principles, sustainable site use, management, fieldwork, fossil and mineral collecting, 1-10. <http://www.progeo.se/progeo-protocol-definitions-20110915.pdf>.

## **“Il Cammino” of the Montefeltro’s Duke: a cross-section of geological and human history in the heart of Umbria-Marche Apennines**

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**Keywords:** Northern Apennines, Umbria-Marche Succession, mobile GIS, sustainable tourism.

“Il Cammino” of the Montefeltro’s Duke is a cross-section of geological and human history in the Umbrian-Marchigiano Apennines that starting from Urbino, UNESCO World Heritage Site, and the cultural capital of the Italian Renaissance passes through woods, countryside, mountains, and villages to reach the medieval Gubbio where Federico the future Montefeltro’s Duke was born.

A Team of the University of Urbino made up of geologists, historians, archaeologists, sociologists, and economists, together with CAI (Club Alpino Italiano), which has provided a small but significant economic contribution (Terre Alte Research Fund 2021) proposes and develops a project to define this new way. It passes through places, such as the Furlo and Bottaccione Gorges, which are very famous not only among geologists. The geological history that starts from 200 My and reaches the present, crossing time and telling of mass extinctions, climate change, and much more is well exposed here and it is just waiting to be disclosed. The Gubbio - Urbino geological cross-section encloses all these stories, as well as the history of man and the culture which developed in these places. The great landscape charm resulting from the interaction between man and nature has provided the raw material for the main artists: Ariosto reports on Furlo when he describes the places of *Orlando furioso*; Torquato Tasso composes his *Ode al Metauro*; Raphael portraits the Candigliano valley in his paintings; Dante tells about Fonte Avellana on the slopes of Monte Catria in *Divina Commedia*.

In addition to the tracing and survey of geo-touristic peculiarities carried out also involving students of different courses of the University of Urbino, tools for communication and spreading of knowledge have been developed, such as an informative geological map of paths and geological and geomorphological points of interest of the Furlo Nature Reserve, together with digital aids (BOT on Telegram: “furlo\_geo\_bot”).

The “Cammini” are “*a slow mobility network giving the country a veritable green infrastructure and offering the ability to travel throughout Italy on foot*” (MIC - <https://www.turismo.beniculturali.it/home-cammini-ditalia/atlante-dei-cammini/>), cross regions that are often wrongly treated as marginal, to tell stories, which become a tool for sustainable and responsible tourism development. The project, which starts from a tale of the geological history that crosses the human one, aims to promote the territory by providing alternative chances for sustainable economic growth of entrepreneurial realities (touristic, artisanal, eno-gastronomic activities) often small but very rich in hospitality and typicality of the high lands of this part of the Apennines.

Attention to the social impact of the path takes concrete form in the intention, right from the conceptual phase, careful to cross, together with geological and historical emergencies, even the wounds that have been inflicted on the landscape by non-sustainable development choices. At the same time, the engagement of a multidisciplinary team is aimed at developing tools and methods for detecting both the economic and social impact of the journey itself through mapping techniques of institutional and associational activities and realities that can contribute to the involvement and synergies at a territorial level. In this way we want also to enhance the synergies that can be created between this and other projects promoted by educational agencies, associations, and businesses in the area.

## Soapstone in the Alps. Usage in the exploitation areas

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Keywords: Soapstone, Alps, alpine Geo-heritage.

Soapstone is a product category that groups metamorphic rocks consisting mainly of chlorite, talc, magnesite and serpentine. Such lithotypes are characterized by high resistance to thermal changes and slow accumulation and transfer of heat, a relatively low hardness (1-4 on the Mohs scale) favouring the processing by hand and on the lathe and a low porosity (limiting the absorption of liquids). From literature the term soapstone has often been extended to all greenstones, lithotypes sharing similar thermal characteristics but very different mechanical parameters (Mannoni et al., 1987). In this way greenstones with soft, fine-grained components and homogeneous structure were used to provide vessels whereas those with harder minerals and non-homogeneous structure were sawn and worked for the production of slabs for stoves, millstones and architectural elements. All these lithotypes belong to ophiolite complexes deriving from the Alpine metamorphism of rocks constituting the oceanic crust emerging in the internal sector of the Alpine chain. The main outcrops and exploitation areas are located in the Valli di Lanzo, Val d'Aosta, Valais, Valsesia and Val d'Ossola; Gotthard- and Aar- massivs; Val Chiavenna and Val Malenco. The exploitation and use of soapstone is known since antiquity, as already mentioned by the Greek philosopher Theophrastus, then by Plinio il Vecchio citing this stone from some Alpine regions in his *Naturalis Historia* (first century AD). In the whole Middle Ages and, subordinately, in the Modern age, soapstone was widely used from several Alpine source regions for production of vessels for cooking and preserving food, the construction of stoves, lamps, architectural elements of baptisteries, fountains and gravestones. In this time interval, the Alpine soapstone vessels reached the regions to the south of the Po Plain, mainly the central Adriatic and Tyrrhenian coast (Santi et al., 2018). The soapstone materials were of very common daily usage also accompanying the life of the Alpine populations from baptism to burial (Pfeifer, 2018), and are therefore important elements in the cultural heritage for all the communities in which these rocks outcrop.

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Pfeifer H.-R. (2018) - Le patrimoine de la pierre ollaire en Valais/Suisse. In: Fantoni R., Cerri R. & De Vingo P. (Eds.), *La pietra ollare nelle Alpi. Coltivazione e utilizzo nelle zone di provenienza. All'insegna del Giglio*, Firenze, 99-104

## The Maiella UNESCO Global Geopark designation as source of new perspectives and policies for Geo-heritage and Sustainable Development in Italy

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Keywords: geopark, unesco, geoheritage, Gustav Line, mining, geo-itineraries.

The Maiella National Park (MNP) has been included in the UNESCO Global Geopark (UGGp) Network last April 2021. Its territory extends over three of the four Abruzzo provinces, and includes 39 municipalities, mainly mountain villages, that constitute a unicum in terms of human interaction with the landscape. For the tight relationship between territory and inhabitants of the area of the Maiella Geopark through centuries, the Maiella mountain has been named “Holy Mountain” or “Mother Mountain”. Signs of human settlement trace back to the Palaeolithic Period in the Valle Giumentina geosite (Demangeot J. & Radmilli M.A., 1953; Nicoud et al., 2016; Villa et al., 2016). In the Maiella UGGp area, 95 geosites have been identified, 22 of which are of international interest (Liberatoscioli et al., 2018). The Maiella UGGp represents a territory with a particular geological heritage, dedicated to a sustainable development strategy, as such it can play an active role in the economic development of the territory. Sustainable tourism can rely on a network of over twenty visitor centres, museums, and 1200km-long network of trails and mountain bike routes. The Maiella UGGp is actually promoting the setting of two different new trails, one related to the Second World War, the other to the Majella Mining Basin. The first one will include the territory of five municipalities and trace the route of the Gustav Line, a German defensive system built at the end of 1943 (Garzarella et al., 2019). The second one will follow the story of the mining activities in the northern sector of the Maiella UGGp (Lipparini et al., 2016). The use of new technologies in touristic offices (i.e. augmented reality, oculus quest) will improve the attractiveness of the trails, in turn supporting the economy of the involved municipalities and inhabitants.

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## **The UNESCO Dolomites geological heritage: present challenge and future opportunity**

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*Keywords:* geology, geo-heritage, UNESCO, Dolomites.

The Dolomites are recognized as a UNESCO natural World Heritage site since 2009. The Geological heritage operating network of the UNESCO Dolomites Foundation ([www.dolomitiunesco.info](http://www.dolomitiunesco.info)) is a team of provincial/regional administrations (Provincia autonoma di Bolzano, Provincia autonoma di Trento, Provincia di Belluno, Regione del Veneto, Regione autonoma Friuli Venezia Giulia), the MUSE of Trento, the Parco Naturale Adamello Brenta Geopark, the Parco Naturale Paneveggio Pale di San Martino, and academic departments (University of Ferrara and University of Padova) representatives. With specific expertise in geology and geomorphology, this network is devoted to conservation, communication and enhancement of all the geological aspects of the property, implementing both long-term planning and immediate practical actions.

Currently active projects are devoted to enhance the incredible geological legacy to the Dolomites, which is also the origin of the landscape we can see today: (i) geological map of the UNESCO Dolomites (1:150.000 scale); (ii) Dolomites World Heritage Geotrail (field guides for geo-tourists); (iii) Dolomites World Heritage Geotrail Immersive View (online spherical 360° image navigation of stunning geological landscapes from drone images); (iv) identification and cataloguing (georeferenced inventory) of geological excellences; (v) degree awards and other initiatives on enhancement, conservation and research; (vi) geomorphological map of the Brenta Dolomites (in progress).



## Fossils of Slovenia

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*Keywords:* macrofossils, biostratigraphy, Paleozoic, Mesozoic, Cenozoic.

On the occasion of the 75th anniversary, the Geological Survey of Slovenia published the book “Fossils of Slovenia - A Look into the Past for Reflection on the Future”, authored by Jurkovšek and Kolar-Jurkovšek, which comprises 263 pages, 33 plates with fossils and 411 cited works.

The book presents a selection of Slovenian fossils that are important for understanding the geological time and environment in which rocks containing fossils were formed, and consequently for knowing the geological structure of Slovenia. The emphasis is on macrofossils, i.e. those that are already visible to the naked eye without optical or electronic aids.

In the introductory chapters, in addition to some basics of paleontology, the path from the earliest evolutionary ideas to the beginnings of paleontology as an independent scientific discipline is presented. The emphasis is on the modern understanding of fossils, their importance for biostratigraphy and paleoecology, and for the development of modern evolutionary thought.

A minor part explains the geotectonic definition of Slovenia, which is located at the junction of the Southern Alps, Dinarides, Eastern Alps and Pannonian Basin. The most extensive part is devoted to geological, biological and climatic events on Earth from the Precambrian to the present day. Part on each geological period provides data on important fossils and their finds in Slovenia, which define rocks by age, paleogeography and paleoecology. It is therefore a kind of biostratigraphic walk through the geological history of Slovenia.

All geological periods are balanced according to their duration, spread of sedimentary rocks in Slovenia and frequency of fossil finds. The selection of localities and fossils is largely subjective and depends on the level of research. Moreover, a large number of additional research data are available for the Cenozoic formations, which are economically somewhat better researched in Slovenia due to the deposits of non-metallic mineral raw materials.

The key reason for writing the book Fossils of Slovenia is that fossils are an important part of Slovenian (and world) natural heritage, which in the past, together with numerous collections of fossils scattered in various institutions in Slovenia and abroad, have often disappeared or been destroyed over time; we know about them from mentions in the older literature. In this book, all important studies of Slovenian and foreign researchers of fossils found in Slovenia are taken into account.

Once it used to be that the present is the key to understanding the past, but today in geology the other paradigm that learns us the past (in many cases) is the key to understanding the present (and probably also to predict the future) is equally valid. Therefore, it is worth thinking what the human species has to offer in the future, especially with regard to climate change.

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## The use of paleogeographic reconstructions as a vector to increase the visibility of archaeological and geological heritage

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Keywords: paleogeographic maps, geoarcheology, GIS.

The Apuan-Versilia plain (northwestern Tuscany) is a dynamic territory subject to continuous environmental evolution and characterized by a widespread archaeological heritage of considerable importance (Bini et al., 2013). In Versilia, tourism is mainly seaside with a concentrated flow in the summer with overcrowding problems (Marchi et al., 2021). However, the cultural and environmental visitor centers located in the immediate hinterland are still poorly known. The study of the environmental evolution (from prehistoric times to today, up to possible future scenarios) could be used as vector to enhance the cultural heritage of the Versilia area as a whole. This work would like to identify past palaeogeographic scenarios by integrating data from different sources (archaeological, historical, cartographic, geological, environmental) into the GIS environment. These paleogeographic maps can be used to connect the various archeological and geological sites located throughout the territory and therefore increase their visibility and importance. This could increase of visits in cultural sites could be help on the sensibilization of the visiting and the citizens on the themes of the cultural heritage and climate change. In fact, the effects of climate change, including global warming and sea level rise, are particularly relevant for coastal areas (IPCC, 2018), such us the study area, where climate change threat cultural and environmental heritage.

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Marchi V., Raschi A., Martelli F. (2021) - Evaluating perception of sustainability initiatives invested in the coastal area of versilia, Italy. *Sustainability (Switzerland)*, 13, 1-13. <https://doi.org/10.3390/su13010332>.

## Geoarchaeology of the Venice lagoon: strongholds, paradigms and a look forward

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*Keywords:* Lagoon, relative sea-level rise, underwater archaeology, geomorphology, palaeoenvironments, geophysics, remote sensing, archaeometry.

Lagoons are dynamic geomorphic systems that depend on the interaction among several processes, e.g., relative sea level rise, longshore drift, wave and wind direction/intensity, recurrence/magnitude of extreme weather events and sea surge. Lagoon sedimentary successions provide continuous archives of environmental change that reflect both autocyclic processes and allocyclic forcing. Lagoons are very productive loci of biodiversity and have long been exploited by human communities for hunting, fishing and mollusk gathering, as well as, in more complex societies, for specific economic needs of, e.g., salt production and fish farming. With the development of seafaring, lagoons have been offering harbor for coastal navigation along otherwise unprotected, low sandy coasts.

The Venice lagoon is a paradigmatic case study of colonization and exploitation of a vast barrier-and-lagoon system. It has been inhabited since the Iron Age at the least, and the anthropogenic impact on the natural system has become overwhelming during the last centuries. A geoarchaeological research approach seems capable of offering insights on past environmental changes, allowing as well a wider comprehension of the long-term anthropogenic impact on the landscape, be it intentional or unintentional.

Our ongoing multidisciplinary investigations focus on some major archaeological sites/clusters of the northern Venice lagoon, i.e., Altinum (Mozzi et al., 2016), Scanello (Canal, 2013), Lio Piccolo (Goti Vola, 2019) and Canale San Felice (Canal, 2013; D'Agostino et al., 2020). A major effort has been devoted to the integration of diverse methods such as archaeological survey and underwater archaeology, remote sensing and geophysical survey of buried archaeological evidence, coring and analysis of in-, near-, and off-site sedimentary archives, archaeometric analysis of archaeological artifacts and structures, geomorphological reconstruction of major landscape modifications. First results i) show the inadequacy of some former paradigms in the theoretical approach to the lagoon archaeology, ii) highlight some strongholds that can direct the future research agenda, and iii) open new perspectives in the understanding of the diachronic interaction of humans and the environment in these amphibious landscapes.

Canal E. (2013) - Archeologia della laguna di Venezia. Cierre, Verona.

D'Agostino M., Fozzati L. & Medas S. (2020) - Lio Piccolo, laguna di Venezia: indagini, rilievi e operazioni di restauro su un pozzo-cisterna di epoca imperiale. *Archaeol. Maritima Medit.*, 17, 27-101.

Goti Vola V. (2019) - La villa romana della laguna nord di Venezia. Apparati decorativi e contesto archeologico. Il leggio, Chioggia.

Mozzi P., Fontana A., Ferrarese F., Ninfo A., Campana S. & Francese R. (2016) - The Roman city of Altinum, Venice lagoon, from remote sensing and geophysical prospection. *Archaeol. Prospect.*, 23, 27-44.

## Tackling geohazard in populated geoheritage sites

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*Keywords:* geohazard resilience, nature conservation, natural disasters, Dovžan Gorge Natural Monument, Slovenia.

Protected areas of geoheritage which are populated are all faced with challenge of keeping balance between preserving the natural environment and human interventions for living, economic activities and safety.

Dovžan Gorge Natural Monument is one of the most interesting geological sites in Slovenia. With the longest cross-section of fossil-rich Upper Paleozoic rocks exposed it is also one of more significant ones in the Southern Alps. The exposed section of 300–250 million years old rocks enables the study of the paleoenvironmental evolution of the depositional setting and the paleobiologic evolution of several fossil genera (Novak et al., 2019). As such it has high scientific as well as historical and educational value. Geological as well as the geomorphic phenomena were main reasons to protect the area as a natural monument in 1988 (Novak & Mrak, 2020).

The area is part of the Karavanke mountain range and prone to various natural hazards. In historical sources many extreme weather events are recorded. The most recent one occurred in the night of 29-30 October 2018. Extreme rainfall has initiated torrent flows in the Tržiška Bistrica river basin that caused significant changes in Dovžan Gorge particularly in the riverbed. It also caused material damage on the infrastructure.

Historical records reveal similar events that have taken place before and similar response to them (Novak & Mrak, 2019). This allows the assessment of the human perception of natural disasters and historical memory of them. The October 2018 event opened new aspects of nature protection and intensive economically controlled management of natural resources, in this case primarily forest. In the 2 following years interventions on slopes and in riverbed with heavy construction works severely intrude into natural environment and processes. The Dovžan Gorge Natural Monument has thus proven to be an excellent polygon for the study of natural processes and anthropogenic impacts. It therefore serves as a case study for balancing nature conservation, human activities and geohazard mitigation in geoheritage sites.

The research is co-funded by the Slovenian National Committee of UNESCO, Internat. Geoscience Prog., grant No. C3330-21-456004, and its project IGCP 692 - Geoheritage for Geohazard Resilience

Novak M. & Mrak I. (2019) - Aspects of the consequences of the extreme weather event in the Dovžan Gorge Natural Monument. *Geologija*, 62(1), 123-135.

Novak M. & Mrak I. (2020) - Natural Monument Dovžan Gorge: Geology and geomorphology. Geological Survey of Slovenia.

Novak M., Forke H.C. & Schönlaub H.P. (2019) - The Pennsylvanian-Permian of the Southern Alps (Carnic Alps/Karavanke Mts.), Austria/Italy/Slovenia - fauna, facies and stratigraphy of a mixed carbonate-siliciclastic shallow marine platform along the northwestern Palaeotethys margin. In: Herbig H.-G. (Ed.), 19th ICCP, Cologne, July 29-August 2, 2019: field guides. *Kölner Forum Geol. Paläont.*, 24, 251-302. Inst. Geol. Mineral., Uni. Köln.

## **Geoheritage and geodiversity: an integrated path between Geoconservation, enhancement of natural assets, dissemination and geotourism**

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*Keywords:* Geodiversity, geoheritage, geoconservation, enhancement, dissemination, Friuli Venezia Giulia.

The distinctive geodiversity and geoheritage of our territory are unique assets which preservation is under constant threat. The unawareness of this problem increases the risk of losing important evidences about the evolution history of our planet and its living systems.

For that reason, we aim to promote an integrated path between geoconservation, enhancement of natural assets and information dissemination in close cooperation with relevant Public Authorities.

Within this framework we present an ongoing strategy of the Geological Survey of the Friuli Venezia Giulia Region: following an initial geosite's inventory, we moved toward the implementation of a specific local legislation including protection measures but mainly enhancement tools such as the institution of specific regional grants. A recent upgrade of the specific Regional Law 15/2016 concerning the "Protection and enhancement of regional geological and speleological heritage" recognized also the need to operate directly in the territory where geodiversity is worth to be enhanced. To support this, a local network, called "Geodiversity functional network" was created and the promoters were identified to coordinate the activities of the Local Authorities operating in the sector, through its competent Geological Survey.

Above mentioned actions are supported by communication and dissemination activities for all age groups including primary and secondary schools, adult public as well as training of geological guides and creation of suitable geotrails, which are essential for the development of a sustainable geotourism.

All this increases the value of the territory itself and stimulate, as an indirect spin-off, a general respect and constant protection of the environment, keeping in mind that, when something is understood and comprehend, it is easier to appreciate and consequently protect, so that it continues to exist.

## **Geoarchaeology Role in the Urban Environmental Analysis: Rome's landscape anthropic transformations**

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*Keywords:* urban environment, anthropic transformations, geoarchaeological data, landscape reconstruction, Rome.

The heavy urbanized areas are characterized by the close relationship between Earth's processes and human activities, here the historical human presence and its industry modelled the landscape. Geosciences and Archaeology, sharing the space and time analysis of an area, analyze separately or in collaboration the one and the other element of this relationship. In collaboration case, geoarchaeology uses geoscience techniques in the archaeological record analysis.

Thus, geoarchaeology strongly supports the urban environmental analysis, especially in Mediterranean cities, characterized by thousands years of natural and artificial substrate stratification. Rome city is an emblematic case. In the context of the city urban geomorphological analysis, based on anthropic transformations reconstruction, objective of this work are the analysis of geoarchaeological literature about the city center, the data classification and the collection of informations about landscape anthropic transformations. This study focuses on the south est area of Rome historical centre, collecting papers about archaeological, geognostic and stratigraphic surveys, paleoenvironmental reconstructions, geomorphological and hydrogeological investigations. The collection of geoarchaeological scientific literature is systematized by scientific topic, area of interest, historical period, kind of data obtained for the landscape reconstruction. Anthropic transformations in the landscape results from the geoarchaeological literature analysis, some examples:

- local geomorphology transformations due to land use changes: modifications of drainage network, valleys artificial fillings, deviations or opening of channells for use by mills, excavations or burials of ditches;
- landscape anthropic evolution due to changes in land use: i.e. mining activities in the ancient period, replaced by filling depressions over the centuries to gain surface for settlement or agricultural use; removal of the structural surface for levelling;
- historical transformations of the tributary valleys of the Tiber river in response to hydraulic risks occurred due to eustatic changes in late antiquity;
- succession of several chronological surfaces in the subsoil, due to landfilling;
- space-time hydrogeological variations and potential impact on archaeological remains by 3D geological model implementation and hydrogeological risk surveys;.

The results obtained demonstrate how geoarchaeology supports the urban geomorphological analysis aimed at city planning and management, heritage protection and valorization.

## The Cavallone Caves geotrail project: explaining the Majella UNESCO Global Geopark

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Keywords: hypogene karst, carbonates, central Apennines, geotourism.

The neo-born Majella UNESCO Global Geopark hosts more than one hundred mapped caves, some of which represent important geosites and touristic attractions. Underground karst systems are often excellent environments to investigate and characterize the stratigraphical relations, tridimensional spatial organization of geological structures, morphologies, and fluid flow pathways in the subsurface, as well as to reconstruct paleosismology, paleoclimate and landscape evolution over geological time.

The Cavallone Caves geosite (CCG), in the southern sector of the massif, is one of the most important cave systems of the Geopark, being a tourist attraction since 1893, and as such one of the earliest show caves in Italy. This cave is part of a km-long inactive hypogene karst system formed by the rising of H<sub>2</sub>S-rich fluids, which turned into sulfuric acid in the oxygenated cave environment close to past water table. This site was recently investigated with a multidisciplinary approach involving structural geology, petrography, mineralogy, geochemistry, and geomorphology. Our geological investigations allowed to reconstruct the deformation history affecting this sector of the Majella massif and to unveil the main sources and the permeability pathways able to channelize rising H<sub>2</sub>S fluids from depth (Pisani et al., 2021). The geomorphological observations and the analysis of the conduits' spatial organization indicate the presence of multiple phases of sub-horizontal karst development, reflecting the migration of the sulfuric water-table and the uplift of the Majella massif over time. The oldest (highest) cave level has been dated with <sup>40</sup>Ar/<sup>39</sup>Ar geochronology on secondary alunite to 1.52 +/- 0.28 Ma, marking the exact timing of speleogenesis (and thus water table position) at the time of formation (D'Angeli et al., 2019). Furthermore, fault zones and hypogene karst conduits constitute a network of high-permeability structures for secondary and tertiary migration of hydrocarbons, as proven by the presence of bitumen-impregnated speleothems and hydrocarbon manifestations in the cave and surrounding outcrops. The CCG and its extraordinary location proved to be a perfect laboratory for karst sciences, structural geology, geomorphology, and a significant outcrop analog of deep hypogene karstified reservoirs. Furthermore, its touristic character makes it an ideal site to explain and promote the geodiversity of the cave and its surroundings, which covers multiple aspects of the Majella geological heritage.

D'Angeli I.M., Nagostinis M., Carbone C., Bernasconi S.M., Polyak V.J., Peters L., McIntosh W.C. & De Waele J. (2019) - Sulfuric acid speleogenesis in the Majella Massif (Abruzzo, Central Apennines, Italy). *Geomorphology*, 333, 167-179.

Pisani L., Antonellini M., D'Angeli I.M. & De Waele J. (2021) - Structurally controlled development of a sulfuric hypogene karst system in a fold-and-thrust belt (Majella Massif, Italy). *Journal of Structural Geology*, 145, 104305.



## Origin of Tuscan architectural bricks a multidisciplinary analyses

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Keywords: bricks, mortars, Tuscany, river Arno.

Since the Middle Ages, Pisa was a very important center for the production of tiles and bricks using the clay of Arno and Serchio rivers. Our study focused on bricks sampled from 15 buildings (both religious and civil) aged between the 12th and 17th centuries in Pisa and its neighboring territory. Investigation of iconographic and cartographic sources, together with mensio-chronological measurements were carried out to ascertain the chronology of the constructions. Typology of the mortars and binders of the wall hangings were further studied. We note that archaeomagnetic analyses on these brick ensembles were also carried out as part of this project (Genevey et al., 2019). In thin section, the mixtures of the bricks are homogeneous, while different textural features are present, allowing grouping by morphology and granulometry of the binder and by the reciprocal relationships between the different components. The use of the same raw material, maintained for a very long time, is evident. These are artifacts obtained starting from a clayey material containing silicate debris largely attributable to quartz both in single crystals and in polycrystalline aggregates with a morphology from sub-angular to angular, and therefore not attributable to the addition of sandy components. This fact seems to indicate, rather than a supply from the Arno sediments, a source of the raw material from the deposits of smaller watercourses. The isotropic red-colored matrix due to iron oxidation - due to the firing of the bricks in furnaces with excess oxygen (oxidizing environment) at temperatures between 800 and 980 °C - are common to all the samples, and the presence of recrystallized calcium carbonate, that involved calcareous fragments probably added to increase the porosity of the building and reduce its weight. The calcareous inclusions have a fine granulometry and are evenly distributed in the mixture, while the quantities of limestone are variable. The qualitative composition is homogeneous, while the relationships between silicon and calcium change. The comparison of the textural and compositional characteristics of the bricks of Pisa with those of the Calcinaia bricks shows considerable similarities. Based on these results we can hypothesize the origin of all these bricks from the area of Calcinaia where the presence of brick kilns is documented since the XVI century and where the nearby presence of the Arno river made transport in the city of Pisa easy.

Genevey A., Principe C., Gallet Y., Clemente G., Le Goff M., Fournier A. & Pallecchi P. (2019) - Refining the high-fidelity archaeointensity curve for Western Europe over the past millennium: Analysis of Tuscan architectural bricks (Italy). From: TEMA, E., DI CHIARA, A. & HERRERO-BERVERA, E. (eds) *Geomagnetic Field Variations in the Past: New Data, Applications and Recent Advances*. Geological Society, London, Special Publications, 497, 73-88. <https://doi.org/10.1144/SP497-2019-74>.

## Geoconservation in Sicily: the example of Isola delle Femmine (Palermo, Italy)

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Keywords: geoheritage, Panormide Carbonate Platforms, Cretaceous, mammillary calcite.

Our contribution aims to describe the geological aspects of one of the natural reserves from northwestern Sicily, known as Isola di Fuori, and erected as a geosite by the Sicilian Region.

Isola di Fuori, also known as Isola delle Femmine, is a small island along the Tyrrhenian coast, about 10 km NW from Palermo. It falls in the integral protection zone of the Marine Protected Area Capo Gallo-Isola delle Femmine, between Punta Raisi and Capo Gallo. In 1997, Isola di Fuori, was erected as Oriented Natural Reserve by the Sicilian Region and at the same time was entrusted to LIPU (Italian League for Bird Protection). As most of the northern sector of the Palermo Mountains the island consists of Mesozoic carbonate successions pertaining to the Panormide Carbonate Platform. In the northern sector, of the Island dolostones and dolomitic limestones of uncertain age (?Upper Triassic) crop out, while the southern zone consists of well bedded gray limestone of Lower Cretaceous age. The two units are in contact through a low angle normal fault. These units are unconformably covered by patches of Pleistocene calcarenites and, in turn, by eluvial-colluvial deposits.

Macro- and microfacies of the Lower Cretaceous gray limestones are typical of inner carbonate platform environments including tidal flat and lagoon. The most common facies are stromatolitic bindstone, foraminifer and algal packstone and mollusk floatstone. Their stacking patterns are typically peritidal cycles.

The geoheritage of Isola di Fuori include the “worm trottoir” and calcite/aronite mineralizations.

The “worm trottoir” or “worm reef” is an above-water bioconstruction, typical of the Mediterranean Sea, produced by vermetid mollusks (*Dendropoma* sp.) associated to red algae (e.g. *Neogoniolithon* sp., *Lithophyllum* sp.), which follows the sinuosity of the shoreline.

Peculiar calcite mineralizations are globular-shaped mammillary calcite, a type of speleothem that forms on the roof or overhanging walls of submerged embedded rocks. Other spheroidal calcitic bodies, described as shelfstone, are typical of karst pools. The abundant presence of this type of calcite, together with other speleothems such as stalagmites and crusts, is indicative of the presence of karst cavities now dismantled by the coastal erosion. All the geological peculiarities have been included in a “Map of the Isola di Fuori geosite”.

Besides the geological features, anthropic remains include the Camilliani’s tower “Torre di Fuori”, built in the 16th century on the highest point, which attributes the name to the island and from which are born popular legends, and the remains of seven cocchiopesto tanks, dating back to the Hellenistic period, used for the preparation of garum, a sought-after fish sauce traded in the Mediterranean.

## **Following a water drop: an immersive geotouristic itinerary in the “Sassi”, the rupestrian old town of Matera (Basilicata - Southern Italy)**

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*Keywords:* Sassi di Matera, rupestrian town, Gravina canyon, urban geotour.

The “*Sassi*”, the Italian word for stones, is the name of the surprising rupestrian old town of Matera in Basilicata (southern Italy), characterized by the excavation of a complex network of caves, tunnels, cisterns, houses, and churches, dug in carbonate soft-rocks. This stunning rupestrian scenery, whose first human settlement dates back to the Palaeolithic, has been included in the UNESCO World Heritage List since 1993, and was designated as the European Capital of Culture 2019. Due to its features, Matera has been the location for several movies, including the “Bond 25 - No time to die”. >As a consequence, Matera is attracting a large number of tourists fascinated not only by the cultural patrimony of the old town, but also by its rural setting.

The *Sassi* (the old town of Matera), the *Gravina di Matera* (the canyon along which the *Sassi* developed), the “*Murgia Materana*” (the almost barren karstic plateau incised by the canyon), and the clayey hills on which the modern districts spread, represent a unique opportunity for an urban geotour while walking from the main square of the town down to the bottom of the *Gravina di Matera*. An example of just how fascinating, and feasible, this tour could be is to trace the course of water from the clay hills of the new town. Here remnants of ancient gravelly-sandy flat deposits host an aquifer that originally fed springs located above the old urbanized side of the *Gravina di Matera*. These springs, now completely buried below the buildings of the new town and almost forgotten by the local inhabitants, fed the old town where water was stored in small (domestic) or very big (public) cisterns. The latter have now become an underground touristic attraction in themselves (i.e. the “*palombaro lungo*”, located under the main square of Matera).

In conclusion, some selected stops along historical paths within *Sassi* could offer the opportunity to admire the amazing geology of the area, and to learn about the geological reasons for the particular urbanization of the old town of Matera.

## **MurGEOpark (southern Italy): the last piece of Adria, the (almost) lost continent!**

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*Keywords:* Geopark, Murge, Pre-Murge, Adria.

Murge and Pre-Murge (Apulia, Southern Italy) is part of Adria, the plate “squeezed” between Africa and Eurasia from when these two continents began to converge. Deformed Adria rocks are widely distributed in the orogens surrounding the Mediterranean Sea, and in many newspaper and magazine articles as well as online videos, Adria is described as “a lost continent”. Even if this definition is “scientifically incorrect”, the idea of the lost continent is very attractive, also because in Italy there is a region where a small part of this lost continent still survives. This region corresponds to the Apulia Foreland where Murge represents the central area. Here, structural, sedimentary, geophysical, magnetostratigraphic, geochemical attributes of the only Adria crustal rocks that are rooted on the mantle in their original position can be studied. Within plate tectonics, Murge can be considered as the first piece of a puzzle whose location in the original painting (the Adria Plate) is known.

In 2019, based on this premise, the executive of the Alta Murgia National Park (southeastern Italy) decided to propose its territory as possible inclusion in the network of the UNESCO Global Geoparks. Since then, in cooperation with the Department of Earth and Environmental Sciences (Aldo Moro University of Bari) and SIGEA, it is working to candidate the area as an aUGGp (called “MurGEOpark”).

Following the leitmotiv of Adria, in the MurGEOpark, the Cretaceous evolution of the continent is spectacularly recorded in Alta Murgia thanks to the limestone succession of one of the largest peri-Tethyan carbonate platform (the Apulia Carbonate Platform). The MurGEOpark comprises also the adjacent Pre-Murge area, where the southwestern lateral continuation of the same platform, being flexed toward the southern Apennines mountain chain, is thinly covered by Plio-Quaternary foredeep deposits. The Plio-Quaternary stratigraphic and morphotectonic evolution of this foredeep is spectacularly exposed thanks to an “anomalous” regional middle-late Quaternary uplift.

The worldwide geological uniqueness is that the area is the only in situ remnant of the Adria Plate, but the international value of the proposal is enriched by the presence of several geological singularities such as two paleontological jewels of very different age: a Neanderthal skeleton preserved in speleothems within a karst cave, and one of the largest surfaces in the world with upper Cretaceous dinosaur tracks (about 25.000 footprints). Moreover, the close relationships between man and geology are spectacularly documented in the MurGEOpark: among the others, the use and conservation of water in a karst area, the prehistoric and ancestral choices of urbanization, karst caves traditionally used as religious sites, the magnificent use of local rocks in the building of white cathedrals, castles and old towns, etc. All these examples demonstrate how the MurGEOpark could offer a good opportunity to spread the geological culture to a wide and diverse audience.

## **The enhancement of the geological heritage of the Taburno-Camposauro Regional Park as an opportunity for sustainable development in Campania (Italy)**

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*Keywords:* Geoheritage, Regional Park, Southern Apennines.

The Taburno-Camposauro Regional Park extends for almost 137 km<sup>2</sup> in the internal areas of Campania. The park includes the mountain ranges that give it its name, which are located in the southern segment of the Apennine chain, as well as their foothills. Belonging to this segment is evident from the geological history, which can be read in the outcrops of the rocks, in the form of the landscape and in the surface and underground waters present in this area. The same history of man, who has frequented these places from very long times, seems to be embedded in these characteristics, indeed over the centuries man has appreciated the advantages of using these assets.

In fact, as it was not possible to detect in the eastern Camposauro, the beauty of the shallow marine limestone outcrops of the middle Cretaceous. In that period these limestones were found suddenly emerged and therefore subject to phenomena of atmospheric degradation, so they were altered and corroded. The filling of the cracks and cavities with residual deposits has caused these rocks to assume polychrome colours mostly of various shades of red. Soon they became the object of mining, and today these worked stones, called “marbles”, adorn the monumental buildings not only in Italy (Caserta, Naples, Rome), but also abroad (France, England and even Russia).

But how can we forget among the geological assets, the richness of the widespread karst forms of the Taburno and Camposauro. Those present on the highest plateaus are represented by sinkholes and polje, which are still frequented today by flocks and herds of one of the oldest activities in these territories: the breeding. While, the numerous caves that open on their slopes, not always entirely attributable to karst phenomena, were places of worship and devotion, or a refuge for shepherds, brigands and hermits. Today in some of them we recognize the “footprints” they left behind (eg the 12th century rock paintings).

Another aspect that should not be underestimated is water. In addition to the numerous small springs scattered almost everywhere in the Park area and the hydrographic network that diverges from the reliefs to extend to the surrounding plains to feed the precious crops of the territory, the water spring of the south-eastern side Taburno known since Roman times. They were once so abundant that they fed the western coastal areas with monumental aqueducts, also recognized by UNESCO.

These geological assets, mentioned above, are just some of those present in the Park heritage, which could be enhanced to ensure not only their protection, but the development of economic and tourist activities in an internal area. In fact, the position of this area places it in constant marginalization. Such enhancement integrated by the variety of ecosystems as well as other cultural, gastronomic and intangible heritages in the Taburno-Camposauro Regional Park could represent a real development opportunity for the present and for future generations.

## Multidisciplinary geoininerary in the Cilento, Vallo di Diano and Alburni Geopark (southern Italy)

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*Keywords:* geosite, geomorphosite, geo-itinerary, Cilento, Vallo di Diano and Alburni Geopark.

The Cilento, Vallo di Diano and Alburni National Park, fund in 1991, is one of the largest Italians Geopark. It gains the title of Geopark in 2010 and the title of UNESCO Global Geopark in 2015. The Geopark is placed in the southern sector of the Campania Region (southern Apennines). It spans from the Tyrrhenian coastline (where flysch units of the Cilento Group outcrop) to the inner mountainous landscape (where carbonate rocks are largely diffused). Rock-type have locally high scientific relevance and related landforms often have undisputed scenery beauty (Santangelo et al., 2005). Despite the high scientific interest of the Geopark, just few papers highlighted the role of Geotourism in the Geopark by proposing thematic geo-itineraries (Santangelo et al., 2015, 2020; Valente et al., 2020). These papers focused on a specific scientific theme that could be extrapolated by geosites, such as coastal modification (Santangelo et al., 2020) and karst landforms (Santangelo et al., 2015; Valente et al., 2020).

In this paper, we have carried out a comprehensive analysis of all 160 geosites listed in the official catalogue of the Geopark with the aim of proposing a multidisciplinary geoininerary. The multidisciplinary geoininerary aims at increasing the interest towards sectors of the Geopark not usually included in classical tourist routes, e.g., the inner sector of the Geopark. To select the geosites to include in the geoininerary, we have applied the Brilha (2016) method by assessing the potential Educational (E) and Touristic (T) use of each geosite. Geosites have been ranked according to both the E and T uses, with ranks ranging from 1 to 4. Geosites whose rank exceeded 3, and that have not been included in already published geo-itinerary, have been included in the geoininerary.

The obtained multidisciplinary geoininerary starts from the Paestum archaeological site, to the west, and then move to the Calore River WWF Oasis and the abandoned town of Roscigno, and other less known geosites, in the central sector of the Geopark, to end in the Vallo di Diano lacustrine basin, to the east. The proposal of this geoininerary may shade lights on the amazing inner Cilento areas and may help the increase of local economy with the possible development of outdoor activities focused on Geotourism, and thus possibly reducing the abandonment of small villages by young people.

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### **3GEO – Geoclimbing & Geotrekking in Geoparks: a new UNESCO IGCP project for geoheritage communication and education**

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**Keywords:** Geoparks, Geoclimbing, Geotrails, Multimedia surveys.

Geoheritage is increasing its global and local importance not only as a scientific research topic, but also in relation to socio-economic activities that can benefit from Georesources. In this context, sites of geological interest may represent hot-spots for outdoor activities connected to Earth Sciences (e.g., geotourism, hiking and climbing). The UNESCO IGCP 3GEO project aims at offering innovative digital tools for geoheritage and geoscience communication through geoclimbing and geotrekking activities. In particular, climbing and trekking sites within established or aspiring geoparks, and other natural areas, have high geoheritage potential (Garcia-Rodriguez & Fernandez-Escalante, 2017; Ruban & Ermolaev, 2020), and are also suitable for education activities as well (Bollati et al., 2018). The goal of this project is the development of multimedia tools for geoheritage and Earth Science communication (Perotti et al., 2020) through a global network of iconic geoheritage sites equipped for climbing or featuring trekking trails. These sites include UNESCO Global Geoparks or natural areas (e.g., PARNA Chapada Diamantina, Kütralkura, Estrela, Psiloritis, Rocca di Cerere, Sesia Val Grande) in countries (Brazil, Chile, Greece, Italy, Oman, Portugal, South Africa, Spain) spread over four continents. Climbing cliffs and trekking routes are selected according to scientific and cultural, aesthetic and socio-economic values and their employability. A set of innovative geomatic techniques (e.g., 3D photogrammetry, Structure from Motion, Unmanned Aerial Vehicle surveys) are the tools for displaying and communicating geoheritage properties along selected geocliffs and geotrails. These web-based multimedia materials (e.g., 3D model of climbing cliffs) will be shared out among different users (e.g., schools, universities and general public) both for virtual reality and outdoor activities. The multidisciplinary and multicultural context of the 3GEO project is the key for a 360 degrees' experience of geoheritage in Geoparks or natural protected areas, taking into account accessibility issues and global travel restrictions.

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## **The Dolomites World Heritage Geotrail: travelling geological landscapes**

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*Keywords:* Geotourism, Field guides, Immersive photography, Dolomites.

The Dolomites World Heritage Geotrail is a currently active project of the Geological heritage operating network of the UNESCO Dolomites Foundation. It is aimed at making a wider public discover the geological landscapes of the Dolomites, through a series of thematic field guides and immersive views from stunning aerial drone images. On one hand, four thematic guides describe the geotrail itinerary, which depicts the shape of a spiral ammonite fossil from the Brenta Dolomites to Monte Pelmo. On the other hand, a set of 27 viewpoints (immersive spots) is distributed across the nine dolomitic systems, in order to describe both the long-lived geological history of these mountains and their very recent events. From atolls and reefs of Triassic age to Quaternary landforms, from past mass extinctions to present-day natural disasters.

The dolomitic landscapes are incredibly attractive because of their magnificence and beauty. However, they are also extremely able to tell us of events, facts, histories, environments which are visually depicted at many scales in space and time. Their language is made up of colours, shapes and matter. The pages of their book are many millions of years or few seconds long. Each stage of the geotrail and each immersive spot contain specific geological elements which can be discovered one by one, combined to form a trip on the geological history, from lithogenesis to morphogenesis, or about catastrophic nature and climate changes. Virtual geotourists can appreciate the landscapes they observe and also motivate the choice to visit the Dolomites face-to-face.

## **Beached swords from the Marano lagoon (northern Adriatic) reveal ancient land-sea connections and recent coastal evolution**

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*Keywords:* swords, Marano lagoon, Northern Adriatic, Middle Age-Modern Age, major hub, coastal erosion.

Likewise other tidally-influenced environments, depositional and erosional processes, subsidence and sea-level changes have strongly modified the coastal landscape of Northern Adriatic lagoons over last millennia. Such rapid transformations induced significant consequences on the human settlement and, consequently, on the archaeological visibility of the area, which is still largely unexplored.

We present here six metal finds fortuitously retrieved by fishermen in last decades in front of the barrier islands of the Marano Lagoon. The finds, immediately recognized as swords by their shape, were covered by a thick concretion mainly constituted of sand and coastal shell. Moreover, two items were inserted into a wooden sheath.

Multi-analytical analyses carried out on the artefacts (X-ray radiography, laboratory- and synchrotron-based X-ray computed microtomography, radiocarbon dating and typo-chronology) combined with the study of the coastal paleo-environment (mainly based on historical cartography and remote sensing) allowed to define the main features of the items and to shed light both on the historical importance of the area as well on the significant morphological changes occurred in this coastal sector over the last millennium. For the first time, we are able to interpret an historical map of the 16th century, drawn by the Venetian cartographer Cristoforo Sabbadino, that depicts in detail the shoals along the coast and reports a unique wooden structure located in the sea, in front of one of the tidal mouths entering in the Marano Lagoon.

The presented data indicate that the Marano Lagoon represented a major hub in Northern Adriatic during Late Middle Ages and early Modern Age connecting inland Europe with the Mediterranean. Moreover, the research highlights the onset of coastal erosion occurred in the last century after a phase of relatively geomorphic stability, possibly deriving from the intensification of human impact and climate change.

## **The Etna Park geotrails network: new digital tools to know and learn the geological peculiarities of the volcano through nature trails**

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*Keywords:* geotrails, volcano, education, geosciences, nature paths.

Nature trails are one of the preferred didactic laboratories to carry out differentiated teaching of geoscience for various classes, as they are particularly indicated both for primary school students who read and describe nature, and for high school ones who develop interpretations from the initial observations.

The constant growth of innovative technological supports has made available new tools that make contact with nature increasingly immersive and experiential, even in the field of learning geosciences. In this context, the entire Etna Park geotrails network, which consists of 50 nature trails, has been completely digitized making available online through the website and an android/ios app, all the information previously available only on paper. In this way, the description and geolocation of each element of geological interest such as caves, lava fields, hornitos, pyroclastic cones, and so on, are easily accessible and at hand for conducting laboratory activities directly in the field.

Within this framework, a pilot didactic geotrail was selected as a guide path on which to model the remaining nature trails that insist on the Etna area. In this pilot geotrail, in fact, various peculiar elements of the volcano have been identified which are particularly suitable for didactic activities directly in the field, for each of which the relative descriptive panel has been developed and affixed along the path. These educational activities play a crucial role in bringing people closer to geosciences as they allow to incentivize students to enroll in geology courses and to develop a wider sensitivity and culture for the environment.

## **Geo-heritage, geoparks, geo-itineraries are the normal/temporal evolution of the concept of “Geosites”, Opened problems in Italy.**

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*Keywords:* geosites.

After 25 years from the II Symposium on Geological heritage, held in Roma on 1996, which developed a national attention on the geosites, many interventions were carried out either at Regional or National level, such as inventories and protection measurement. On the other hand we have verified the flourishing of new ways of seeing and interpreting the problem of protecting geosites, often linked to the legislative way of protecting them. Thus, was born the concept of Geodiversity which has little to do with that of Biodiversity, but since there are strong legislative instruments for the protection of biodiversity, it was thought that such tools could also be used in the geological field. It is clear to all that a granite is different from a limestone or a clay. If we add to this the concept of Geoparks, UNESCO Areas, geotourism and geoitineraries, we completely lose sight of the concept of geosite, which often has not an areal development, such as to be able to make a park, but remains a witness to time, which it is for science and not for mass tourism. The legal instruments to protect the nature, from a general point of view are, connected with the “System of protected natural areas” (National Parks; Regional and Intraregional Natural Parks; Natural Reserves; Wetlands of international interest; Other protected natural areas; Terrestrial and marine retrieval areas). This legislation shows strong limits if applied to geosites, because if the word geology appears in some cases, the word geosites do not appear specifically. The archaeological superintendencies have a strong instrument to protect palaeontological sites but only in some cases (where lithic industries or Neanderthal skulls were not present) in all national territory applied a constraint on the land. This confusional regime has created the abandonment of specific geosites to speculations of various kinds and consequently to their destruction. This is the case of Cava Tacconi, near Pomezia (Rome), where in addition to a complex geostructural situation, linked to the semigraben of Ardea, there was a malacological association with 171 species of molluscs, with 4 Nordic guests, typical of the Lower Pleistocene (Emilian). A building development for 1500 apartments is now planned on this site.

## Sharing of the criteria and methodology for the management of the national geological heritage

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*Keywords:* geological heritage, geosites, inventories, guidelines.

In 2018, ISPRA, Geological Survey of Italy, with the intent to coordinate all geological institutions, created the Italian Net of Geological Surveys. This is a connecting structure between the Geological Survey of Italy and all Regional technical institutions, Autonomous Provinces and ARPA. The operative structure dictates the establishing of round-table discussions, namely Tables, dealing with geological themes. The Table concerned with geological heritage compares the experiences of 18 Italian Regions and one Autonomous Province in the field of the knowledge and protection of regional geological heritage. Currently, the advancement of different regions is distinctly disparate. This is especially in the inventory of geosites, which is the basic instrument for the study of geoheritage. Hence, the Table, based on the experience of each region in safeguarding geosites, designated a small group to redact guidelines, both technical and practical. These guidelines are to be used in local inventory and to safeguard and promote regional geosites. The debate considered geosites as geological assets to be safeguarded, as they are representative of “geodiversity” rather than “cultural heritage,” as designated in the Urbani Code. Moreover, it offered the opportunity to separate the term “landscape” and the term “geosite”. In the past, when there was a lack of specific laws, the term allowed to safeguard geosites using the planning and legislation that regulated cultural and environmental heritage (Urbani Code, territorial and landscape planning). Today however, this term appears limiting.

In the National Inventory of Geosites (ISPRA), geosites are currently considered of international, national, regional and local interest. This classification is based on scientific criteria and it is then combined with the distinction based on the prevalent geological characteristics of each site. This distinction determines that a geosite can be categorised as geomorphological, paleontological, etc. This framework determines that the sole term “geosite” should be used, defining said geosite afterwards, using its prevalent scientific characteristic (i.e. geomorphological geosite, palaeontological geosite, etc). Other terms present in literature, such as “geomorphosites,” “archeogeosites” and “geological emergencies,” should be abandoned. In accordance with the European Tables, it is necessary to examine the identification and classification criteria of the Global Geosites Project, so as to verify its applicability to the Italian situation. The method defines the categories of geosites of international, national and regional level and dictates the identification of geological frameworks. The geosites are recognised in the light of such frameworks through the field work of specialists. Still recognising the validity of the method, in hindsight it becomes comparatively difficult to apply.

An initial version of these guidelines for the identification and characterization of Italian geosites has also been drawn.

## **A project for the protection and enhancement of surface faulting effects induced by the 2016 Central Italy seismic sequence along the Monte Vettore – Monte Bove fault system**

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*Keywords:* geosite, Earthquakes, surface faulting, Sibillini Mounts, Vettore, geological itinerary.

In this note we illustrate a joint project carried out by ISPRA and Monti Sibillini National Park focused on the 2016 Central Italy earthquakes surface faulting enhancement and protection along the Monte Vettore - Monte Bove fault system. The project aims at increasing public awareness to natural hazards within the territory of the park, and to keep the memory of the event through the enhancement of such highly scientific value sites. In fact, the coseismic ruptures induced along the Monte Vettore - Monte Bove fault system by the two main shocks (24 August and 30 October) represent the largest and most documented surface faulting example in Italy.

Three areas have been identified along the Monte Vettore – Monte Bove system to be preserved and to be pointed out with the aim of showing and describe the most evident geological evidences of this geological event: at Colli Alti e Bassi, where the recent coseismic rupture is marked by a white stripe at the base of the fault plane, allowing to estimate the amount of displacement equal to about 60 cm; along the Cordone del Vettore fault scarp, where is possible to observe a total amount of displacement of about two meters high and along a gully in the southern slope of Monte Vettoreto.

The project consists of a geological itinerary marked by ten viewpoints, where information boards illustrate surface faulting phenomena and some other ground effects induced by the 2016 earthquake. Two other introductory panels, in Visso and in Arquata del Tronto, invite the visitors to join the geological itinerary. Those interested in learning more in depth about the 2016 Central Italy earthquake, will be able to access directly from their smartphone to further multimedia web resources (i.e., videos and papers), through a QR code.

The project comprehends also some protection works against weathering on the fault mirrors revealed by the 2016 earthquakes.

## **Coastal geosites and their valorization: a case study along the North-Eastern Italian Adriatic coast**

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*Keywords:* coastal geosites, valorization, geotourism, North-East Italian Adriatic coast.

The coastal environment is increasingly compromised by anthropogenic pressure including touristic, agricultural and industrial activities that take advantage of their proximity to the sea. Also the conservation and the protection of natural elements are compromised in this contest. Among the various natural resources to be safeguarded and enhanced, there are also geological and geomorphological ones which, together with floristic and faunal elements, constitute great value environments, worthy of being protected.

Along the northeastern Italian Adriatic coast, various coastal landscapes as sandy beaches, lagoons and deltas represent a precious and preserved geodiversity.

In particular, the Marano and Grado Lagoon, between the deltas of the Isonzo and Tagliamento rivers, is characterized by the presence of channels, tidal flats, islands and saltmarshes protected seaward by a system of sandy barrier islands.

Here the tide draws a mosaic of brackish wetlands of great value, also thanks to the shallow depth and the high supply of fresh water from the rivers that flow into the lagoon.

Further east, the tidal flats between the mouth of the Isonzo River, the natural eastern boundary of the Grado Lagoon, and the bay of Panzano, extend this articulated and fragile complex of wetlands until the karst cliffs.



## The Atlas of Geosites of Sicily

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*Keywords:* Geological Heritage, World Geosite, Sicily.

Geosites represent the geological, geomorphological, palaeontological, mineralogical or other interests in a territory with scientific and environmental values of the landscape heritage (Wimbledon et al., 1996). Generally, geosites are natural architectures, or singularities of the landscape, which testify to geological processes that shaped our planet. They provide an indispensable contribution to the understanding of the geological history of a region and represent values of exceptional importance for the landscape and cultural, educational and recreational attractions.

With the regional law N. 25/2012 and the subsequent decree of the Department of Territory and Environment (D.A. n. 87/2012), Sicily adopted a specific regulation for the establishment of the “Regional Catalog of Geosites”, and the identification of the procedures for the establishment of the single Geosite. The Catalog originally contained over 2400 geological emergencies surveyed with varying degrees of completeness. Pending their establishment, these emergencies have been defined “Geosites of attention” while the term “Geosite” was reserved only for emergencies that would have been established with a specific decree. Nine years after the publication of the law, the Sicily Geosite Catalog includes:

- 93 “Geosites” established in the Nature Reserves of geological interest (D.A. 283/2017),
- 17 “Geosites” set up by a single D.A.;
- 4 “Geosites” to be established;
- 339 “Sites of geological interest” (which will be progressively established),
- About 2000 “Warning Sites” (sites whose rarity and representativeness requirements must be confirmed by studies and scientific studies to be subsequently included in the “Sites of geological interest”).

We now propose the creation of an Atlas of the Geosites of Sicily and smaller islands. The geosites to be treated are organized in groups and subgroups including sedimentary basins, geomorphological, tectonic and metamorphic features, volcanic districts, fossiliferous and karstic geosites. Each group and subgroup would be preceded by a brief introduction by one or more authors. The list of geosites follows with Name, Location, Coordinates, Degree of scientific interest, Primary scientific interest, Category (Areal, punctual, linear), State of the Geosite (Established, to be established, sites of geological interest). The atlas represents an ideal tool for those who want to orient themselves in the discovery of geosites in one of the most complete regions of the world from a geological point of view.

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## A geopark on Karst plateau – a transboundary project

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*Keywords:* Classical Karst, transboundary geopark, karstic geoheritage, cross-border cooperation, Karst.

The carbonate plateau between Slovenia and Italy, known as the Classical Karst (in Italian Carso Classico, in Slovene Matični Kras) is the universal symbol of the karst phenomena. It's characterized by all type of surface and underground karst forms, with such particular density, wideness and typology to recall the first researches of what will then be called "karstology", from the name of this area: Karst, Kras, Carso.

There were and there are several proposals for the enhancement of the Karst geological heritage, many and different scientific publications, as well as a lot of dissemination and touristic outputs and, it has become necessary to provide a coordination and settlement, from a geological point of view.

This is the reason why the Geological Survey of the Friuli Venezia Giulia Autonomous Region, representing the municipalities of the Italian side, and the Municipality of Sežana, representing the municipalities of the Slovenian side, are working together for development of a cross-border geopark on the Karst plateau between Slovenia and Italy and its candidacy to the UNESCO Global Geoparks Network.

In compliance with the agreement relating the establishment of the geopark in the Slovenian part of the Classical Karst (Matični Kras) signed by the five Slovenian municipalities on 1 October 2015 and the letter of intent signed by the 12 Municipalities of the Italian side of Karst, for the establishment of a geopark on the territory of the Italian Classic Karst on 14 September 2017, on 23 April 2018, was signed the Agreement for the establishment of the cross-border geopark in the transboundary territory of the Classical Karst by the mayor of the municipality of Sežana (representing the municipalities of the Karst in Slovenia) and the Regional councilor. Since this transboundary agreement, numerous activities have been carried out by the two parties for the development of the geopark.

Finally, starting from middle of 2020 this joint project received funding from European funds with a new project of the Interreg program Italia-Slovenia V-A 2014-2020 named GeoKarst - Establishment of the Cross-border geopark on the Karst. It was developed on the fourth programs axis "Enhancing capacity building and cross-border governance". The pandemic global crisis has negatively affected the timing of the planned activities, so the duration of the project was extended by six months. The final goal of the project is to consolidate the joint transboundary works for a joint candidacy of the Karst in the UNESCO Global Geoparks Network.

Since it's known that geology has no borders as well as the geological and cultural heritage on Karst plateau, a transboundary geopark will certainly help to joint the area from the scientific view and that of the local sustainable development. Several international projects, developed on this cross-border area such as Hydrokarst, Roof of Rock, Carso-Kras have already shown that it works.

## The functional recovery of the Poggio la Vecchia Quarry: an Example of Geo-Heritage conservation

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Keywords: quarry, Manciano Sandstone, functional recovery, geo-heritage, conservation.

The Manciano Sandstone consists of medium to very coarse, fairly well-sorted, lithic to lithic-arkosic sandstone, with calcite cement, and minor intercalations of sandy conglomerates. It represents a key lithostratigraphic formation for the interpretation of the Miocene stratigraphic and structural evolution of the Tyrrhenian sector of the central-northern Apennines. This formation crops out discontinuously over the Ligurian Units in northwestern Latium and southern Tuscany, and two geosites have already been identified: along the S.P. F32 Farnese-Manciano, in the Tuscany Region, and along the Latium coast (Bagni di S. Agostino). The best exposures are observable in some quarries near Manciano (Gamberaio, Poggio la Vecchia, Scarceta), where a detailed facies analysis has been carried out (Rossi et al., 2017). However, access to these sites is generally not allowed during mining activities, and when this activity ceases, the quarry fronts are buried in order to proceed with the environmental recovery of the area. We think that in this case, the scientific interest of the outcrops should be considered prevalent compared to a traditional morphological recovery, often obtained with questionable results. On this basis we present a possible functional recovery of the Poggio la Vecchia quarry. Along its fronts, which develop over 80 m in height, the diamond cut walls show extraordinary exposures and, at the end of quarrying, an area of about 9ha could be preserved for geo-touristic itineraries, exalting the beautiful and unique landscape, and the panoramic views on the beneath Fiora valley. The regularization of the quarry fronts would allow each floor to be used in its completeness, without discontinuity, and in safe conditions. The geodiversity of these outcrops allows a wide range of possibilities for scientific dissemination and information, with particular emphasis on sedimentological and paleontological topics. The most common structures include medium-scale cross-stratification formed by the migration of 2D and 3D dunes (tabular- and trough-cross-bedding) and small-scale cross-lamination formed by the migration of waves and current ripples, as well as well preserved ichnofacies (*Macaronichnus*, *Ophiomorpha*, *Skolithos*, *Cruziana*, etc.) and interesting paleontological content, with layers containing oysters and echinids (*Scutella striatula*, *S. leoganensis*, *S. paulensis*). Another peculiarity is the presence of Liesegang rings, whose genesis is related to the main fracture systems affecting the rock bodies. In each of the identified stops, it will be possible to get a simple explanation of its peculiarities through information totems or Q.R. code. It would be desirable that this type of recovery project was also extended to the other two quarries that could form together with the near geosite an extended geopark.

Rossi F.G., Madonna S. & Milli S. (2017) - Facies Analysis Applied To Quarrying. *Procedia Engineering*, 208, 136-144.

**S27.**  
**Geology, food and health**

*CONVENERS AND CHAIRPERSONS*

*Giancarlo Ciotoli (CNR IGAG)*

*Carlo Ferretti (Geo Identity Research - GIR)*

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## Link between drought climatological indicators and asthma in the general population

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Keywords: asthma, drought, climate variability, human health.

Asthma is a main chronic respiratory disease worldwide, affecting over 330 million people of all ethnic groups throughout all ages. In the US, asthma is one of the most common and costly diseases and it is responsible for more than 5000 deaths annually. An association between climatic conditions (drought) and asthma mortality has been widely assumed. However, it is unclear whether climatic variations have a fingerprint on asthma dynamics over long time intervals. The global environment has been facing large changes during the last century, which can also affect respiratory health with increased asthma frequency worldwide. According to McCabe et al. (2004), spatial and temporal variances in multidecadal drought frequency over the contiguous US are attributable to the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) interaction. In view of the statement of the Global Asthma Network, we hypothesized that drought and asthma mortality may show similar periodicity in the contiguous US. To detect a possible correlation between drought and asthma mortality rates annual data (from 1950 to 2015) of asthma mortality were downloaded from the US National Center for Health Statistics. AMO and PDO data were downloaded from National Oceanic and Atmospheric Administration. The analysis of the signals was performed by applying the Empirical Mode Decomposition algorithm of Huang et al. (1998). To compare the dominant periodicities (asthma versus AMO versus PDO) we applied a bandpass filter. We found that asthma death rates evaluated in 4 different age groups share the same pattern of fluctuation throughout the 1950-2015 time interval, but different trends. Annual asthma death rates turned out to be correlated with the dynamics of the AMO, modulated by the PDO, and sharing the same averaged ~44 year-periodicity. The results of the current study (Bonomo et al, 2019) have suggested an influence of climate patterns on asthma mortality rates in the US. This has prompted us to assess whether a similar association may be found for asthma incidence in Italy. A collaborative research (within the domain of the "One Health" concept) using data from the Italian branch of the European Community Respiratory Health Survey is ongoing to find a possible relationship of asthma incidence with drought indices.

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## Soil functional factors of Italian wines

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*Keywords:* soil, geology, geomorphology, wine, terroir.

The study of the relationships between the natural characteristics of the environment and the quality of the wine highlights the existence of a specificity. The basic element of the viticultural vocation is the territory, which materializes in a geographical space within which the work of nature and the centuries-old intervention of man have given rise to a food that cannot be produced elsewhere, whose qualitative excellence manifests itself continuously, therefore even in the most difficult years. It is from the interaction between natural and human factors that the peculiarities of wine are born. The high number of different areas dedicated to wine production is to be considered an element of the value of Italian viticulture, together with the great wealth of national varieties. The analysis of the various factors that lead to the qualitative expression of wines has been the subject, in the last twenty years, of numerous scientific studies, which have highlighted in the first instance, i.e. on a fairly large geographical scale, the fundamental contribution that geology and the geomorphology contribute to the peculiarities of the wine-growing areas. These factors contribute to determining the characteristics and qualities of the soil, some of which have a decisive effect on the viticultural and oenological response. In particular, the characteristics that condition water and mineral nutrition, such as water retention capacity, depth and volume that can be explored by the roots, stoniness and colour (mirror of its chemical composition), superficial and deep drainage, richness in active limestone as well as in macro and microelements, they are the basis for the quality of the grapes and the subsequent qualitative expression of the wines.

Wine-growing areas located on fissured and karstified limestone rocks, which favour the removal of excess water through deep drainage, often have a high viticultural vocation. Where the parent material is calcareous marl, the soils are generally clayey and silty, retain a good amount of water and give finesse to the wines, while the granites and sandstones produce sands and gravels by alteration, which dry out very easily and contain vigour. Soils on volcanic basalts, rich in nutrients, give an imprint of robustness and fullness to the wines. Soils on alluvial sediments rich in clay are suitable for vigorous vines and wines with character.

The best terroirs are rooted in soils where for most years the crop yield is moderate but of good quality, without a massive integration of chemical fertilizers and unsustainable risks for the conservation of soil quality.

## **Vineyards and clay minerals: multi-technique analytical approach and correlations with soil properties**

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*Keywords:* vineyard soils, terroir, clay minerals, quantitative phase analysis, cation exchange capacity, mixed-layer clay minerals.

Purpose of this research is to quantitatively assess the mineral component of vineyard soils, with particular attention to the mineralogical analysis of clays, which represent an element of high importance in the vineyard culture as well as in general agriculture.

An X-ray diffraction (XRD) / thermogravimetric (TG) multi-technique analytical approach was developed, tested on soil samples taken from vineyards around the world. This codified analytical procedure was necessary to obtain precise qualitative and quantitative mineralogical data, globally comparable to distinguish the geopedological identity of the vineyards. Soil samples from vineyards of various locations were analysed, in very different geological conditions. The bulk-rock quantitative phase analysis (QPA) was obtained by the Rietveld method while the detailed composition of the clay-sized fraction was determined by modelling of the oriented X-ray diffraction patterns.

The research provided a precise classification of the mineral component of soils, distinguishing the mineral phases of the clays and the so-called mixed-layer clay minerals. We found that the content in mixed layers can be directly correlated with the water retention and the cation exchange capacity of the soil, while the presence of other clayey minerals and phyllosilicates in this research did not affect this CEC parameter, which codes the fertility level of the soils.

The study demonstrates that terroir, in particular soils formed in complex or very different geological conditions, can only be effectively interpreted by properly analysing its mineral phases, in particular the mixed-layer clay component. These are characteristic abiotic ecological indicators, which may have specific eco-physiological influences on the plant.



## **Geology and food quality: research and results on ecological indicators that shape terroir and wine quality**

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*Keywords:* Geology, Food, Wine, Quality, Terroir, Ecological Indicator.

The environment of a given place is causally linked to both the ecological diversity and plants phenological processes, which are particularly evident on grapevines. The wine quality depends on the many ecological features that make up the so-called “terroir” of the vineyard. Some of these are directly linked to the vineyard geological origin, e.g. soil mineralogy and physico-chemical properties, pH, moisture and water availability, land geographical characteristics including topography, altitude and insolation. In order to detail the geological argument and measure its ecological importance, these many factors need to be evaluated separately in a quantitative and comparable way. This procedure can precisely classify individual ecological factors and to compare their influence on both the behaviour of grapevine and the wine quality.

Recent researches on more than 26,000 vineyards in the South Tyrol wine-growing region have identified new methods for characterising the geological and topoclimatic identity of a territory. The land suitability can here distinguish zones and geographical units with the most suitable ecological conditions for the different cultivars. Geographical and geo-pedological data have been compared with the centuries-old winemaking experience of the local wine cellars, and with sophisticated chemical-physical analyses carried out on soils, grapes, musts and wines. These made it possible to verify the direct influence of geological terroirs on the different agri-food products. For example a clear correlation between mineral traceability in soils, musts and wine have been confirmed. Research findings measured the direct increase in the musts sugar content related to vineyards topoclimate index. Geological vineyards features linked to wines quality were observed, for instance in the polyphenol content and in some specific aroma precursors component, as well in amino acids and tannins present in musts and wines.

The geology and geomorphology of the wine territory can be rightly included among the local geographical features that serve as natural ecological resources, influence the biosynthetic activities of plants and their phenology, promoting biodiversity and the qualitative predispositions of grapes and wine.

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Ferretti C.G. (2020) - L Nuova classificazione sperimentale per la zonazione dell'Alto Adige DOC. *Vite e vino - L'informatore agrario*.

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## The Maiella UNESCO Global Geopark: from geodiversity to biodiversity, a journey through environmental and agricultural conservation.

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*Keywords:* geodiversity, biodiversity, UNESCO, global geopark, bioclimate.

The Maiella UGGp is characterized by a biodiversity heritage among the most significant in Europe. The floral wealth of the Majella, in both quantitative (the high number of species present) and in qualitative terms (many endemic, rare, or endangered species) is the result of complex geologic and climatic events. Human agropastoral activities, conducted in the past in non-intensive ways, contributed notably to this patrimony, with the creation of new habitats and ecological niches (Conti et al. 2019). Maiella UGGp established in 2005 its own seed bank, together with the R.I.B.E.S. network (national network of 15 seed banks) focused on wild, rare or endemic species, which are threatened with extinction, and on native varieties (Di Martino et al., 2015). It aims the conservation of plant germplasm, as part of the in-situ conservation activities in the botanical gardens of the park or in the sites of farming designated keepers (Di Cecco et al., 2020). The strong relationship between the landscape and humans led to preserve some varieties almost disappeared (Di Martino et al., 2020). Maiella UGGp is trying to recover them, being the link between the need to ensure environmental conservation and the natural, agricultural and food traditions, and the guarantee for sustainable development (Di Santo M. & Di Cecco M., 2015). The Maiella UGGp and the wine producers Cantina Orsogna, pursue a common project to select indigenous yeast strains from the mountain flora at different altitude ranges, in different bioclimatic zones. Once collected, the pollen is poured on sterilised must. After the subsequent multiplication of yeasts, the wine producers allow the grapes to ferment with indigenous yeasts. The result of this long and hard process is an organic biodiversity-certified wine (Zulli et al., 2020).

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## Tracing the provenance of Tuscan Extra Virgin Olive Oil using Sr isotopes and Rare Earth Elements

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**Keywords:** EVOO, petro-chemical tracers, Sr isotopes, REEs, traceability.

A promising method to trace the geographical provenance of products of the agro-food sector consists in using petro-chemical tracers derived from the geological substratum of the production area. The radiogenic isotope <sup>87</sup>Sr is one of the most robust tracers used. Indeed, Sr is ubiquitous in rocks and soils at ppm levels. Its isotopic composition depends on the parent/daughter ratio (<sup>87</sup>Rb/<sup>86</sup>Sr), the age and the origin of the bedrock. Another possible geochemical tracer is represented by REEs (Rare Earth Elements) patterns, which varies depending on the geological and petrological setting. Pelacani et al. (2017) showed that the REEs and the <sup>87</sup>Sr/<sup>86</sup>Sr are absorbed from soil and transferred to the olive pulp of *Olea Europea*, without any significant elemental and isotopic fractionation, meaning that <sup>87</sup>Sr/<sup>86</sup>Sr of plants and fruits reflects the <sup>87</sup>Sr/<sup>86</sup>Sr ratio of the bioavailable soil fraction.

In order to assess if Sr isotopes and REE patterns can be used as geographical tracers also for olive oil, we investigate sixteen olive groves from different geological and geomorphological setting of Tuscany, located in Chianti, High Tiberina Valley and Maremma. Particular attention was paid to minimize local differences in climate, topography, and cultivar. Samples of soil, olives and extra virgin olive oil (EVOO) were collected from each olive grove.

The main challenge is represented by the low content of REEs and Sr in EVOO, especially for Heavy REEs with concentrations < 4 pg g<sup>-1</sup>. We set up in our lab a procedure to extract REEs and Sr from olive oil and olives involving mechanical stirring and ultrasound assisted extraction (Turk et al., 2019), followed by Sr purification using standard chromatographic techniques. <sup>87</sup>Sr/<sup>86</sup>Sr measurements in soil, olives and olive oil were performed by TIMS, while the REE content was determined by ICP-MS. Preliminary results suggest that this analytical procedure is able to concentrate more Sr and REEs from EVOO, allowing more precise measurements.

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## Mapping the Geogenic Radon Hazard Index of Italy

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Keywords: geogenic radon, machine learning, geogenic radon hazard map.

Radon production from rock and soil and its migration toward the surface along geological faults are natural processes that can favor radon entry in buildings, thus constituting a health risk. The analysis of these two processes and the construction of spatial models, as the contribution of different proxies of the geological radon source (GRS) (e.g., geology, soil properties, radionuclide content), and of the geological radon migration (GRM) pathways (e.g., faults, karst) in the subsoil, can be used to construct a geogenic radon hazard index (GRHI) map as a tool to predicting the susceptibility of an area (Radon Priority Areas, RPA) to increased indoor radon concentration for geogenic reasons. Many direct and indirect models (e.g., deterministic and probabilistic) have been used to create GRHI maps of a certain region.

Here, we propose a bottom-up analysis including the integration of different factors (predictors and/or proxies) to construct a GRHI map of the whole Italian territory using a GIS-based (spatial) regression and by weighs their importance. In particular, we fitted a model by using Forest-based classification and Regression tool in ArcGIS based on about 35000 measured soil gas radon concentrations and known values of 8 explanatory variables (i.e., proxies) as a part of training dataset. The tool creates the model and generates predictions using an adaptation of Leo Breiman's random forest algorithm, which is a supervised machine learning method. The model can then be used to predict unknown values in a prediction dataset according to a 2x2km regular grid that has the same associated explanatory variables.

The following explanatory variables are included in the model: U content (Bq/kg) of bedrock (Nogarotto et al., 2017), U content of the soil available from GEMAS (Reimann et al., 2014, <http://gemas.geolba.ac.at/>) and FOREGS database (Salminen et al., 2005; [www.gtk.fi/publ/foregatlas](http://www.gtk.fi/publ/foregatlas)), Fine Fraction (FF%) and Available Water Content (AWC %)(Ballabio et al., 2016), Fault Density (FD, Number of Faults/km<sup>2</sup>) from Italian national and regional database, Heat Flow (HF mW/m<sup>2</sup>) (Cataldi et al., 1995) and Karst Areas (KA) from the map of the world karst areas (Chen et al., 2017).

All these predictors were transformed in 2x2km grid maps and then standardised by using fuzzy classification to transform input data to a 0/1 scale. The final map will be used by national and regional authorities to identify the Radon Prone Areas (RPA) as required by the European Directive 2013/59/EURATOM (art. 103).

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## Geochemical characterization and granulometric analysis of agricultural soils as a tool for geographical origin identification: preliminary results from the case study of Massenzatica (Ferrara)

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*Keywords:* food Traceability, granulometric analysis, geochemical characterization, red chicory.

Determination and authentication of the geographical origin of food products have recently become relevant in investigations against frauds for consumer protection. Studies on territoriality are based on the hypothesis that chemical elements detected in plants and their products reflect those contained in the soil. Geographical features of the production area are considered relevant factors affecting the specific designation such as the composition of the parent rock, soil-forming process, climate, topography, and land use. As suggested by Pepi et al (2017; 2018), geochemical characterization, based on the determination of major and trace elements, is commonly used to establish the geographical origin of products.

This work aims to present a preliminary study on soil samples to establish a method to identify the geographical origin of two different types of red chicory (long-leaves and round-leaves). Granulometric analysis and the major element composition, on a set of 12 samples of agricultural soils from the southern Po Delta area were used for local soil characterization. The samples come from a site located in Massenzatica (Municipality of Mesola, Province of Ferrara, NE of Italy) and sampling has been undertaken between October and December 2020 in different fields: 6 samples came from two fields inside the area of the Consorzio Uomini di Massenzatica (CUM), where the other 6 came from an area outside CUM.

Grain size analysis shows a high similarity for all samples, with an average amount of sand of 85.76% ( $\pm 1.47$ ), 10.11% ( $\pm 1.52$ ) of Silt and 4.13% ( $\pm 0.77$ ) of Clay. According to USDA classification, the samples can be classified as Loamy Sand and Sand.

Concerning the major element compositions ( $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{Al}_2\text{O}_3$ ), the samples are comparable, and aluminum plays an important role as a constituent of the clay fraction of soil, as a good reference element. Differences emerge when alkaline elements ( $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ ) are considered: K concentration discriminates in the soil characterization between the two cultivated varieties.

Pepi S., Sansone L., Chicca M., & Vaccaro C. (2017) - Relationship among geochemical elements in soil and grapes as terroir fingerprintings in *Vitis vinifera* L. cv. Glera. *Chemie der Erde*. <https://doi.org/10.1016/j.chemer.2017.01.003>.

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## Possible site-specific effects on wine quality based on various vineyard sites in a heterogeneous area like South Tyrol

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*Keywords:* terroir, vineyard site, grape, vine, wine, wine quality.

Many studies show that grapevines develop differently, depending on their growing area. This phenomenon is shown by the different growth behaviour of the plant. Historical price developments in individual wine-growing areas have led to precisely delimited cultivation sites, down to the smallest sites, forming a pedoclimatic unit, which is identified with the term “terroir” or “climat” or simply “vineyard site”. Often a clearly defined and recognizable wine type is attributed to these units. All over the world, great importance in grape cultivation is given to the grapes’ growth habitat and intensive research of the connections between growing area and wine quality is conducted. In this context it must be considered, that the concept of “terroir” (“climat”, vineyard site) comprises all other viticultural measures which - in part of necessity - shape the cultivation of a particular location. Especially in pedoclimatically heterogeneous areas, like for example South Tyrol, it is a great challenge to recognize and evaluate the site-specific effects due to a multitude of variables. Some exemplary site studies illustrate the impact of the vineyard location on the wine quality. The significance of soil characteristics, geographical situation and microclimate conditions is demonstrated. Possible correlations between individual site characteristics and the types of sensory characteristics are presented and the vintage effect relating to the site-specific effect is defined. The site-specific effect is reflected in the wine quality, which means wines of one grape variety produced in different locations, even if they are very close, show different characteristics. Conversely, wines from different and even distant locations, may show some similarities. Generally, the vintage effect is more significant than the site effect. The climatic and geographic parameters, such as sea level, average annual temperature etc., mostly show more incisive effects than the geopedological parameters (pH-value, grain size composition, etc.). In some cases, however, the importance of these variables could be recognized as well. The greatest challenge in pedoclimatically heterogeneous areas, is the grouping of individual sites into a site unit with certain expected wine characteristics and their delimitation.

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Pedri U. & Pertoll G. (2014) - Auswirkungen unterschiedlicher Standorte auf Trauben- und Weinqualität bei der Sorte 'Gewürztraminer'. *Mitteilungen Klosterneuburg*. 64(4), 156-170.

Pedri U., Pertoll G., Thalheimer M. & Ueberegger E. (2019) - The effects of location on the quality of grapes and wine of the variety Pinot noir. *Laimburg Journal*, 1(Article 10).

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## Temporal and spatial variation for radon concentrations in the Su Mannau cave (Fluminimaggiore, Italy)

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*Keywords:* Radon concentration, trace gases dynamic, passive detector, showcaves, karst critical zone.

Radon concentration in cave may sometimes reach high values depending on bedrock characteristics, cave configurations, groundwater and ventilation. The naturally occurring <sup>222</sup>Rn behaviour in cave environment is of great interest, especially within showcaves where this gas can lead cave workers exposed to high radon activity to a considerable health risk.

In this study, the radon concentration was measured in Su Mannau Cave (Fluminimaggiore, SW Sardinia, Italy) cave atmosphere with the aim to provide a reliable distribution of this trace gas at a spatio-temporal scale. This cave is hosted in Cambrian carbonates belonging to the Iglesiente region, a complex Pb-Zn mining district. It develops for more than 8 km, with large rooms and long tunnels with mostly horizontal profile and only few vertical drops. Cave originated by two different underground streams, that possibly overprints hypogenic speleogenesis. From a micrometeorological point of view, cave atmosphere is well connected with the external one and it is characterised by a mean annual air temperature of 15.8 °C and a relative humidity that approaches 100%. The first part of the cave is equipped for tourist visits and opens seasonally from April to October.

A comprehensive radon survey has been carried out along the tourist path of the Su Mannau cave from February 2019 to April 2020. Radon concentrations were measured with CR-39 solid state nuclear track detectors placed along the cave passages in 6 sampling points distributed over a total distance of about 300 m and a different elevation of 30 m. Each passive Rn sensor has been exposed for 3 months and then analysed by an automatic track reading developed by U-Series Srl (Italy). As carbon dioxide follows radon pattern, CO<sub>2</sub> spot measurements has been performed at each sampling point with a portable device during detectors recovery.

The results reveals that radon concentration ranges from 300 Bq m<sup>-3</sup> to 3,450 Bq m<sup>-3</sup>. The lowest values was recorded close to the entrance and the highest one at the end of the tourist path where the main cave passages is connected to a lateral branch. Over the 4 sampling periods, <sup>222</sup>Rn activity shows significant seasonal variation in each measurement points with the highest concentration in summer and the lowest in winter. The radon activity decreased gradually from summer (June–August) to autumn (September–November) and winter (December–February) and then increased in spring (March–April). This pattern is less evident close to the entrance and more appreciable at the low cave level.

A spatial gradient has been observed along the vertical profile of the cave indicating that there is no equilibrium between the gas mixed with the underground atmosphere. Spatial and seasonal cave CO<sub>2</sub> concentrations followed the same trend. Different factors, such as seasonal cave meteorological effects, groundwater, sediment composition and rock porosity, could possibly influence this pattern. Further investigations could explain this aspect.



## **S28. Geosciences at School 2021**

*CONVENERS AND CHAIRPERSONS*

*Elena Bonaccorsi (Univeristà di Pisa)*

*Francesca Cifelli (Università di Roma TRE)*

*Claudia Lupi (Università di Pavia)*

*Eleonora Paris (Università di Camerino)*

*Manuela Pelfini (Università degli Studi di Milano - Statale)*

## **“How much earth is on my plate?” A special challenge-game to evaluate foods’ ecological footprint**

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*Keywords:* Agenda 2030, ecological footprint, food consumption, team-challenge.

“How much Earth is on my plate?” is a didactic activity that aims to address students to the topic of foods’ water, carbon and ecological footprint and, in a broader view, to encourage them in taking action towards sustainable consumption. The activity has been created in the frame of the Agenda 2030, pointing out the urgent need of a social reorientation towards responsible consumption and production (Goal 12).

“How much Earth is on my plate?” is a learning-by-doing and cooperative learning activity based on a team challenge game. The gaming-challenge approach allows students to engage and enjoy themselves, increasing their own awareness about Geoscience topics such as natural resources (water and soil) exploitation and the carbon footprint due to food production and consumption. The team challenge aims to organize a daily menu throughout the choice of five foods for each daily meal. The winner team is the one that collects a lower ecological footprint menu.

The activity was tested with 45 K7 students, but it is easily adaptable to younger or older students (K6-K8). Students were invited to do a simulated grocery shopping and to work in teams using tools such as food pictures (including labels and packaging), posters, reference data and operational sheets. The team-work allowed students to evaluate, discuss and think critically about the water, carbon and ecological footprints of food and the environmental impact of their transport and packaging.

Pre-activity and post-activity questionnaires were administered in order to evaluate students’ awareness about use of soil, georesources exploitation and ecological footprint related to food production and consumption. Results are very satisfying in terms of involvement of students and show an improvement in pupils’ consciousness on the tremendous environmental impact of food consumption, especially meat as well as imported products. The challenge engaged students in thinking critically about the environmental impact of their choices and how they could change behaviors in an eco-friendly manner. Pupils also discovered that a healthy diet for humans is healthy for our planet as well.

## **Hands-on activities at distance for teachers: difficult but not impossible!**

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*Keywords:* teachers' formation, distance learning, hands-on activities.

In a survey about geosciences and distance learning conducted on Italian secondary school teachers in June 2020 (Borghini, 2020), one of the challenges frequently reported by the teachers was the organization of hands-on activities and laboratories during on-line classes.

In early 2021, we began thinking about how to design and deliver an online teacher Earth science course, maintaining a good level of interaction among participants and providing a relevant space to experiment with hands-on activities that could be replicated with students in school or in distance learning.

Here we present the experience of the course “La tettonica delle placche dietro l'angolo”, which was organized as part of the PLS (Piano Lauree Scientifiche) initiatives of the Earth Science department of the University of Pisa.

The course included four different online activities: seminars conducted by geology professors of the University of Pisa; laboratories dedicated to the use of models, real data and samples observation; didactic planning meetings, and a final meeting in which the participants shared their own “good practices”.

All the participants received at home a kit of rocks that were used during the laboratories, whereas for the other hands-on activities only common and everyday objects were used. The digital didactic materials, as well as the recordings of the meetings, were made available to the teachers on a website.

The data collected at the end of the course through an evaluation questionnaire allows us to say that both the materials and the activities were considered useful by the participants.

Although we all hope that teachers and students could soon return to the real classroom for good, this experience indicates that on-line courses for teachers can have some advantages, such as the possibility to reach teachers that live in different towns and in rural areas.

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## Geosciences and Education: what Role can Libraries play?

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*Keywords:* libraries, education, geosciences.

The two main missions of libraries consist in supporting teaching and research: different objectives that ask for diverse services and collections. Research has increasingly been based on scientific literature in electronic format, and this trend caused libraries to include the management of subscriptions and access to e-journals and bibliographic databases in their services. As regards their educational purposes, libraries make their documental collections available to school and university students as well as to their local communities and citizens in general, thus pursuing the aim of what is nowadays called "Third Mission".

The purpose of our contribution is to illustrate some of the most interesting activities for education implemented by Italian libraries specialized in the area of geosciences, ranging from cartographic reproduction to virtual exhibitions of ancient and rare bibliographic material belonging to their collections, from e-learning courses on information literacy to seminars and book presentations, from internships for schools ("Alternanza Scuola-Lavoro") to collaboration with archives and museums aimed at enhancing documental and material funds of ancient geologists or geological events of the past. Libraries also contribute to the research, retrieval and processing of bibliographic and documentary information relating to particular natural events or landscape evolution.

As their core service for education, libraries work in close connection with the teaching and research staff of their institutions to implement development strategies that keep their collections updated, by acquiring textbooks for course readings as well as specialized bibliographic material for in-depth study, and a broad range of other specific documents that include various kinds of maps and related explanatory notes, field-trip guides, chronostratigraphic charts, photographic material like airborne imagery, theses and reference tools, apart from ordinary books and journals. Contrary to the extreme volatility of electronic materials that are most useful for the continuous updating of research, traditional paper collections are long-lasting for the study of geosciences. Therefore, libraries guarantee their preservation and the constant maintenance of catalogues and discovery tools that can help users to retrieve items of their interest; furthermore, services are offered in collaboration among libraries for reproducing, borrowing, and exchanging documents: document delivery and interlibrary loan boast a long history of cooperation among libraries.

Let this congress enhance it and promote awareness of the important heritage of the Italian libraries of geosciences among their entitled users.

## **The neanderthalian site of Monte Circeo (Italy): an exposition to show the classic work of A. C. Blanc as a geoscience educational tool**

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**Keywords:** education, popularization, invertebrate palaeontology, Mediterranean Sea.

Since the moment in which it has been recovered, the cave Grotta Guattari (Southern Latium, Central Italy) has never ceased to surprise. Located on the eastern side of the Monte Circeo, 5m above the modern sea level, it is part of a complex system of 40 caves dug into the Lias limestone. The cave has been hidden by a landslide for about 50.000 years, until some workmen found the entrance in 1939. The exploration and the study have been carried out by the palaeontologist Alberto Carlo Blanc (1906 – 1960), of the University of Pisa, who found many mammal bones (identified as remains of deer, ox, roe deer, fallow deer, horse and hyena), together with a well-preserved skull of *Homo neanderthalensis*. Recent researches have brought to light many other remains of large mammals and nine other people, dated from 0.1 to 0.05 Ma, pointing at the site as one of the most important of the world for the study of the Neanderthal man.

A.C. Blanc studied largely the geology and the palaeontology of the area between the 1930s and the 1950s, collecting much material from the Monte Circeo (caves of Guattari, Fossellone and Capre), from the Agro Pontino plain, during the excavation of the canal Acque Alte, and from the retrodunal lakes. The collection of fossil invertebrates (mainly molluscs) is stored at the Civic Zoology Museum of Rome, while the vertebrate remains are stored at the Italian Institute of Human Palaeontology in Anagni (Southern Latium). The analysis of the material (partly still unpublished) is of a large interest not only in understanding the palaeoenvironmental evolution of the area, in relation to the sea-level changes (driven by the climatic modifications of the Pleistocene), but also in reconstructing the dynamics involving man during the Middle Palaeolithic: the relationship with the large mammals, the ecological role in the environmental framework, the cultural evolution, etc.

An exposition proposal has been organized with the aim to present the pioneering research of Blanc in a modern perspective, paying attention in illustrating the fossil remains of the Blanc's malacological collection in their ecological and biogeographical background, compared to the present-day climate change. For example, the so-called Senegalese warm fauna (e. g. the bivalve *Eastonia rugosa* or the gastropod *Thetystrombus latus*) allows us to illustrate the long-time evolution of the climate in the Mediterranean Basin, and offer many interdisciplinary links, useful in the frame of the school curricula.

At last, the Mt. Circeo area is a destination chosen by different kinds of travellers: students in class trips, excursionists, tourists, etc. Thus, the exposition, both as permanent installment and as a temporary one, will help to improve the awareness of the public on the importance in protecting and studying the area, but also to focus on the record of climate change in time: an educational tool to understand the future of the planet from its geological history.

## Music analogies for teaching long term changes in Earth's climate

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*Keywords:* climate change, Milankovitch cycles, music analogies, geosciences education.

Climate change is one of the most important topics in geosciences that are cross-disciplinary and relevant for social implications. Teaching activities addressing this topic often focus the students' attention on the potential future effects of climate changes, mainly in terms of global warming. Discussions about the fundamental role of geologic records in reconstructing the Earth's past climate, and understanding its complex dynamics, are generally neglected. The goal of the present research is providing a tool for approaching the study of the long-term records of paleoclimate through the power of music analogies. This offers not only a fascinating way to visualize a complex phenomenon, but also a topic for effective cross-disciplinary teaching.

At the beginning of the last century, Milankovitch computed the incoming solar radiation on the top of the atmosphere as a function of the latitude and from the retrieved cyclical patterns he hypothesized the astronomical control of the Earth's long term climate. Milankovitch's theory could find empirical quantitative support only after Emiliani's and later studies, which established variations in oxygen isotope ratios in the shells found in deep-sea sediments as effective proxies for changes in global ice volume. Hence, only from the second half of last century, variations in the Earth's orbit have been definitely recognized as "pacemaker of the ice ages" (Hays et al., 1976). In the proposed learning environment, characteristic frequencies retrieved from astronomical and paleoclimate time series over last six millions of years have been converted into audio frequencies and the image of a tuning fork is proposed as a music analogue for the forcing role of Earth's orbital motions. Moreover, the dominant astronomical frequencies are converted into orchestral sounds and compared with those obtained from published isotopic records. The same set of data are used to generate amplitude modulated signals, which allows visualizing and listening to the complex natural climate variability. One of the most strong and effective outcomes produced by the musical representations is the clear identification of the sharp change in the dominant frequencies of the isotopic records around 800 ky, which marks the so-called Middle Pleistocene transition. Thus, music analogies are suggested tools not only to facilitate understanding of long term climate evolution, but also for offering a perceptible insight into the complexity of Earth's response, which appears not completely determined by astronomical parameters changes.

Hays J.D., Imbrie J. & Shackleton N.J. (1976) - Variations in the Earth's Orbit: Pacemaker of the Ice Ages. *Science*, 194, 4270, 1121-1132.

## Evaluating the effectiveness of geoscience education in the field: the *Tourinstones* experience

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*Keywords:* Geoscience education, field work, Likert type.

Teaching the Geosciences in the high school is often a complex task and teachers tend to minimize the time dedicated to the Geosciences and/or fail to arouse passion in their students and their appreciation of the importance of the Geosciences for our everyday life. Geoscience teaching is hard also because the basic understanding of the processes active on the planet involve temporal and spatial scales often not perceptible from human experience. In the frame of the PLS project, we designed a field activity to overcome these difficulties and to show the students how, acting like an explorer, may prove fascinating and how the collected data can inform on the main geodynamic processes involved in mountain building and on the time elapsing during these events. The activity is designed on the app *TourinStone*, created by the Earth Sciences Dep. of Turin with the aim of enhancing the ornamental stone heritage of the city of Turin and consisting of several itineraries through the city centre linking the ornamental stones and their provenance from different units of the Alpine chain, and describing the geological history of the Piemonte region. The itineraries were proposed to students from the last three years of the secondary school. Students were asked to describe and identify the main lithotypes occurring in the city centre with the help of a flowchart, a hand lens, and tutors dedicated to the project. A short introduction on how to describe and classify rocks preceded the activity; at the end of the day the students were also invited to hypothesize rock-forming geological processes starting from the basic knowledge gathered from rock observations (e.g. marine fossil content: sedimentary rock originating from the lithification of marine sediments of known age). Moreover, basic discussion on the exploitation of lithic raw material and their sustainability was also addressed during the final part of the activity.

We designed simple questionnaires with 5 Likert-type items to be administered to pupils and teachers before and after the field laboratory. The questionnaires were designed to assess the success of the educational field activity and its effectiveness in stimulating emotional engagement and cognitive improvement in geoscience literacy of the pupils and, their satisfaction with this geoscience activity. Teachers' questionnaires were designed to evaluate the quality and the achievement of the field laboratories, in terms of pupils' disciplinary and soft skill improvement.

The data obtained highlighted how the experience in the field had a positive influence on the perception and interest that students have for the Geoscience and that several misconceptions were solved. Furthermore, the results showed that the students developed soft skills such as observation and judgment as a result of experience. They were able to apply the knowledge and personal skills developed during the activities to respond to the questions in the ex-post questionnaire.



## Teaching Earth Sciences during pandemic time: problems and (some) solutions

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*Keywords:* teaching Earth Sciences, distance learning, Earth's modeling, model of rotation ellipsoid, model of geoid.

The very long period of pandemic has heavily influenced education all around the world. Distance learning (DL) solved the problem in part, ensuring the continuity of the past school years. However, this new kind of schooling was extremely new for most teachers who, for the first time, had to face online platforms as well as streaming for class lectures. Moreover, teachers had to manage shortage of time, even though the topics (school programs) were the same as in normal time. In fact, DL opened a sort of educational new era, including completely new scenarios that forced teachers and more in general educators to renew and adapt most parts of their teaching style in order to grasp the attention of pupils, who stayed at home. At the same time DL had to guarantee a correct information flow to give pupils the opportunity to reach precise knowledge.

In this work we propose some teaching strategies and activities for Earth Science teaching, in particular some distance laboratories that we proposed in the class 1 of Upper Secondary Level (e.g. Italian Prima Liceo scientifico, 14 years old students), during the school year 2020/21. It should be stressed that the first year is a key year in terms of acquisition of a suitable scientific method and often it is the only year in which basic Earth Science topics are learnt.

The activities included building models of rotation ellipsoid and geoid as well and are based on the inquiry approach. In particular, these activities allowed students to focus on and engage in some particularly struggling concepts such as the Earth shape, represented with rotation ellipsoid and geoid, concepts that usually remain obscure also in the following school years.

The activities were organized in learning chunks to avoid overloading students' attention and at the same time to let them better metabolize the scientific contents, with links to other disciplines (physics, maths, art). A final project work assignment involved video recordings made by the students, which was also carried out as formative assessment.

Final results were encouraging: at the end of the unit all students could lead meaningful reasoning about both models and easily distinguish between them to describe the shape of Earth.

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## **An ICT approach to link Geosciences and Sustainability**

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*Keywords:* sustainability, georesources, Virtual Worlds, Opensimulator.

In spite of being often neglected in school teaching, Geosciences are the best link to approach Sustainability and Civic/Environmental Education, being at the basis of most topics of the Sustainable Development Goals (SDG), like Georesources (water, energy, minerals, soil) Climate Change, Responsible consumption, Pollution (water, seas, soil).

Agenda 2030 highlights the importance of education to support sustainability and also to acquire the “Basic skills and competencies needed in the 21st century”. In this framework, ICT (Information and Communication Technologies) can accelerate the approach to the SDGs, through formal, non-formal and informal learning. In this frame, Virtual Worlds (VW) offer great potential as an effective platform for structured paths and collaborative activities to foster learning, improving also students’ involvement.

A virtual island called “Sustainability Hub”, hosted in the VW Techland (Occhioni, 2021) has been created, where students and teachers can access the VW as avatars, communicating and interacting with other avatars and interactive learning objects/external resources/games. “Sustainability Hub” is the starting point for teachers and students to approach Agenda 2030 and SDGs topics. In the island various topics related to sustainability are presented: the importance of georesources and the consequence of their over-exploitation, circular economy, environmental sustainability indicators, an introduction to the Agenda 2030 SDGs. Concepts as water footprint, carbon footprint, ecological footprint, ecological rucksack make students aware of the amount of consumption of natural resources behind the daily products consumed by each person.

A preliminary trial was carried out on a sample of 48 teachers (primary, middle and high Italian schools), which evidenced the effectiveness of this tool to set up educational paths about sustainability. An experimentation was carried on remotely, during the COVID-19 lockdown, with K6-K8 students from 4 schools and a total of 600 students divided between control and experimental group. In a first 2-hours meeting the students mastered the island map, the project aims and tasks to accomplish. In the next meeting, supervised by their teacher and the researchers, they were free to explore the sections, interacting with objects and getting information. The control groups were involved in the same topics but only experimenting the island by screen-sharing in a typical 2 hours lecture.

A questionnaire and final test showed that the experimental group got better scores than the control group, showing involvement and interest in the topics proposed, learning about georesources and waste. Their activity was a tool to socialize with their classmate during the pandemic.

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## **Maps, Earth apps and land images: different tools for different skills**

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*Keywords:* maps, tools, skills.

An analysis carried out on first (11-14) and second grade (14-18) Italian secondary school students and an in-depth analysis carried out in recent years, during the in the different stages of regional and national selections of the Earth Sciences Olympics, and particularly with the students participating in the learning week organized for who will make up the Italian team of the IESO -International Olympiad of Earth Science, highlighted widespread difficulties in the analysis of topographic maps.

The decreasing diffusion of geography teaching in Italian schools, the increasing use of digital tools, apps and software, such as Google Earth and navigators, free and easy to use, has made the use of the topographic maps, and of the various thematic ones, among the students, substantially obsolete.

If the use of digital tools has promoted digital skills, ease of orientation, even greater security in discovering new places, it is leading meanwhile to the loss of skills of observation, analysis and understanding of the context, that only the view of a large area included in a map and not in a few inches of a screen, can give. In reality, both resources constitute a formidable tool, not only for the discovery and knowledge of the territory, but for the growth of specific skills, which are crucial for the knowledge of a territory, but also indispensable in scientific research.

In this research we analyse tools, models and pathways, which foresee the integration of the two resources, and which skills their integrated use can implement.

## Experiments of E-Learning: EAS (Episodes of Situated Learning) during the pandemic

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*Keywords:* Experimental online EAS, Active Learning, Participatory approach, Awareness increasing, Natural hazard.

The need to design engaging and educational distance activities in occasion of special events during the emergency caused by COVID19, has led to experiment the online use of innovative digital teaching methods, previously used in presence for science outreach educational activities for schools. On the occasion of the European Research Night 2020 and on both the World Water and Earth Days 2021, the distance lab activities “Earthquakes: history teaches us the future” and “Tsunamis: history teaches us the future” were thus performed. The activities were carried out by the Istituto Nazionale di Geofisica e Vulcanologia within the European Interreg Italy-Croatia project called PMO-GATE, and within the project FUTURI CITTADINI RESPONSABILI - Cammini Educativi di Responsabilità civile ed ambientale in collaboration with the Italian Associazione per lo Sviluppo SOstenibile e Centro di Educazione Ambientale (ASSOCEA Messina APS). Following the EAS (Episodes of Situated Learning) methodology, complex scientific concepts have been “broken” into small fundamental knowledge that students have acquired in order to be able to transfer these concepts, as a communication product, by means of digital posters, encouraging creativity and the ability of personal processing. EAS was introduced in Italy by Prof. Rivoltella in 2014 and it is structured in 3 phases: preparatory, operative and debriefing, performing the principles of flipped lesson. The researchers were not mere “dispensers of knowledge”, but they were tutors in an assisted laboratory to come up with significant observations and considerations through shared research and reworking of learning by doing activity. More than 3200 students of the third classes of Middle Schools (ISCDE 2) and of all classes of High Schools (ISCDE 3) took part to our events. After an explanatory lesson on past earthquakes and tsunamis, they have become “researchers for a day” and have prepared, independently, 150 creative digital artifacts on some of the most important historical events of their region. Researchers’ knowledge was at service of School using curiosity-driven approaches in order to help homebound teachers and students, adapting the reality of the last year to the difficulties linked to the pandemic. The aim of the activities was to increase the awareness of the risks related to earthquakes and tsunamis through the study of past events, bringing students closer to the world of research and encouraging the personal development of the contents discussed with the experts, to understand how the past is an important key to reduce the impact of future events. Some students have reported their experience with texts they have created on “Noi Magazine”, the insert of Gazzetta del Sud dedicated to education.

## European Geosciences Union (EGU) Education Field Officer programme: a review after two years of activity

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*Keywords:* geoscience education, EGU-IUGS/IGEO, EGU Field Officer programme, Earthlearningidea.

Responding to a widely perceived need for enhancing geoscience education, in 2018 the European Geosciences Union (EGU) launched the EGU and IUGS-IGEO Geoscience Field Officer (FO) programme. Six FOs were selected from Spain, Portugal, Italy, France, Morocco, and India, and trained to run professional development activities based on practical labs following the CASE (Cognitive Acceleration through Science Education) methodology (Adey et al., 1995). These activities, originally developed by the Earth Science Education Unit at Keele University in the 1990s, are published on the Earthlearningidea website (ELI), a continuously growing repository of teaching resources aimed at geoscience teachers without an academic background in this field or needing training in practical geology. FOs began running teachers' workshops in their respective countries in May 2019, providing 21 workshops for about 400 attending from all school levels until April 2020, when the spread of the COVID-19 pandemic precluded the performance of any 'in person' activities. Also, the training of seven new FOs already appointed was postponed for the same reason. After a suspension during the first pandemic wave, FOs resumed their activity by switching to distance training and adapting the format of the workshops with the use of ad hoc presentations and videos autonomously recorded or provided by the Earthlearningidea team. Up at May 2021, 19 on-line workshops were performed in Spain, Portugal, Italy and India, for nearly 600 participants. The outcome of the workshops was assessed by means of a questionnaire administered during the workshops. General interest, professional interest, and interest in attending other similar workshops were rated at the highest level by more of 80% of the respondents. Teachers' comments and requests also evidenced high appreciation for the proposed methodology, specifically for the practical knowledge, and for the trainers. Critical remarks were few, and generally focused on external constraints (Realdon et al., 2020). In addition to the workshops, four teachers' conferences were presented by the FOs and two papers on EGU workshops were published, with one more in press. Geoscience plays an important role in the operation of society and in protecting the future for all humans. Moreover, geoscience underpins key areas of the Agenda 2030 Sustainable Development Goals. The FOs' dissemination activities are helping to fill the gap in the professional development support available to geoscience teachers across Europe and beyond and will result in promoting the adoption of sustainable development models in a growing number of countries.

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## Ocean Literacy (OL) and Sustainability in the UN Decade of Ocean Sciences: current status and perspectives for the Italian schools

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Keywords: Ocean Literacy, sustainability, Italian schools, Ocean Decade.

Ocean Literacy, that is “*an understanding the ocean’s influence on you and of your influence on the ocean*” is at the base of a worldwide movement, born in the US at the beginning of the century and diffusing in Europe since the 2010s by initiative of some NGOs, as EMSEA (European Marine Science Educators Association) and OLI (Ocean Literacy Italia) in this country. Within EMSEA, a guide to the Mediterranean Sea Literacy has been published (Mokos et al., 2020) to adapt the principles of OL at this regional context.

In Italy the status of OL in schools has been only recently addressed by education research, evidencing a complex scenario: sea-related topics are absent in the science curriculum of the 1<sup>st</sup> instruction cycle (grades 1-8) and appear only in high school guidelines, while textbooks include marine issues, with different deepening depending on the school grades. Primary and middle school students’ literacy, though, assessed by regional and multicentric investigations, appears to be moderate on average, with some misconceptions, in accordance with the findings in other European Mediterranean countries (Mogias et al., 2019).

This scenario could be positively influenced by the launch of the UN Ocean Decade of Ocean Science for Sustainable Development (2021-2030). This global initiative has two distinctive features: it addresses science considering the UN Agenda 2030 as a central framework and focuses on the impact of ocean sciences on societies of both less developed and developed countries. OL is recognised as having an important role in spreading the knowledge and in triggering a behavioural change since the early school grades, thus promoting a general improvement of teaching also in Italian schools.

Some other favourable circumstances make this achievable: the introduction of the teaching of civics education in all school grades, with emphasis on environmental education and sustainability, and the launch of large-scale ocean-related education projects, as the EU4Ocean Blue Schools initiative. The European Blue Schools initiative, grounded on existing successful OL programmes as Escola Azul in Portugal, aims at involving as many schools as possible in education projects focused on the environment and developed with local partners. Public communication and involvement of the local communities make Blue Schools projects interdisciplinary and competences promoting. As every school innovation, also the diffusion of OL requires the availability of professional development for teachers. EU4Ocean initiative has already run workshops for all school grades, other training opportunities are being offered by OLI and the University of Camerino.

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## The “QuaderniCIRD” journal. An open access digital resource for permanent teacher training

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*Keywords:* Educational Research, Teacher Training, Science Education, School, University, University of Trieste, Journal, QuaderniCIRD.

Founded in 2010 and published online by the Publishing House EUT - Edizioni University of Trieste, QuaderniCIRD is the multidisciplinary semi-annual magazine of CIRD. Characterized by an ethical-social mission aimed at improving the training systems and the consequent effects on the social systems of reference, the magazine aims to disseminate, at national and international level, research, proposals and innovative teaching experiences for schools of every order and degree and for the University and to develop new forms of collaboration with other similar Centers. Qualifying objectives pursued by the magazine consist in improving the initial and lifelong learning processes of teachers of schools of all levels and of the University, also through comparison with what happens in the training systems of other countries and promoting the national and international diffusion of subsidies useful for improving, supporting and updating teaching / learning processes, also favoring the systematic synergy between School and University. The magazine also intends to encourage the design of innovative vertical and interdisciplinary educational paths, establishing a fruitful comparison and seeking a common language among the various disciplinary education.



## **Arte, estetica ed ecologia: un connubio ad alto potenziale educativo**

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*Keywords:* arte, estetica, ecologia, didattica emozionale, didattica trasformativa, educazione sostenibile.

Per realizzare un'educazione scientifica che porti ad uno spontaneo rispetto dell'ambiente è necessario sviluppare negli studenti un senso di appartenenza e di relazione interdipendente con l'ambiente naturale circostante. Il senso di consapevolezza e di responsabilità è essenziale per riuscire ad attuare un cambiamento duraturo nei nostri comportamenti tesi a una maggiore sostenibilità. A livello educativo è, quindi, indispensabile agire sull'integrazione delle sfere cognitive ed emotive: le emozioni vissute durante attività didattiche coinvolgenti sono strettamente connesse con l'apprendimento significativo di concetti scientifici e con la sensibilizzazione alle tematiche ecologiche. La nostra ricerca didattica si concentra sulla sperimentazione di nuovi modelli di apprendimento integrati e atti a sviluppare una profonda consapevolezza delle relazioni che collegano l'uomo all'ambiente. Attraverso pratiche di espressione artistica e di condivisione emotiva delle esperienze pensiamo di realizzare un insegnamento transdisciplinare, che fornisca diversi punti di vista sul mondo e che stimoli un apprendimento a "tutto tondo", integrando tra loro gli aspetti cognitivi, percettivo-motori ed emotivo-relazionali.

## **Entrepreneurship and communication skills of university students for disseminating geoscience to school**

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*Keywords:* school, entrepreneurship, communication and managerial skills.

Geological phenomena have always attracted young people: events such as volcanic eruptions, earthquakes and landslides, with their unpredictability and impact, interest and worry the communities in which they occur. In particular, in the city of Naples (southern Italy), hundreds of thousands of people live close to Vesuvius and Campi Flegrei volcanic areas. The communities that populate these areas should be aware of the dangers associated to volcanoes as well as they should know that effusive and explosive products accumulated in the past have been used as materials to pave roads and decorate edifices, and may be still used for building purposes. The population should be also informed of the likely benefits derived from geothermal energy. To Earth Sciences researchers and students, the entire Neapolitan area appears an open-air laboratory for risk assessment and resources exploitation, while to many citizens, including new generations, the social, cultural and energetic impact of the geological scenarios over the daily life is still quite unfamiliar. In order to reduce such gap and to promote geo-scientific disciplines, during 2021 many initiatives for the dissemination and orientation of school students have been organized by the Department of Earth, Environment and Resources Sciences at the University of Naples Federico II (Naples, Italy). During the winter term, many seminars devoted to secondary school students have been held to disseminate a wide range of geological topics. All the questionnaires of customer satisfaction proposed to the involved students highlighted a very high degree of interest on the dealt themes, but a general low inclination to choose the degree in Geological Sciences. In order to increase their awareness on the territorial context and to possibly widen the number of students enrolled for a geological academic course, in the spring term, we proposed several programs integrating the seminars with field camp training. Among these initiatives the “Neapolitan Volcanic Project” has been targeted to secondary schools and entirely managed by university students, most of which had previously attended a course on scientific communication and popularization, organized at the Polytechnic and Basic Sciences School of Federico II University. These students chose the scientific contents and suitably selected the field-trip itineraries. We present such experiences and the key elements of the adopted strategies: student-to-student and teacher-to-teacher communications, field camp preceding Earth Science classes, training on scientific communication. We also highlight how managerial skills of university students, gained in other contexts (e.g. congress organization, management of student associations) are pooled as best practices for activities targeted at schools.

## Geoclimbing and Gamification for teaching Earth Sciences in the secondary schools

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*Keywords:* geoclimbing, geoeducation, gamification, 3GEO IGCP UNESCO.

Geoclimbing consists of connecting the free climbing activity with the observation of geological and geomorphological sites of interest. It is addressed to scholars that hence have the opportunity of getting closer to Earth Sciences while experiencing a multidisciplinary outdoor activity. This has been the aim of the UNESCO-IGCP Project “3GEO”, which focuses on the creation of a global network of iconic geoheritage sites equipped for climbing, also suitable for educational activities with schools. In fact, geoclimbing revealed to be very important as a teaching strategy, as it enhances students’ curiosity and makes them participate actively in the learning process (García-Rodríguez & Fernández-Escalante, 2017).

In Italy, this practice has already been experimented in schools, especially in 1st level secondary schools with a project called “Gekologia” conducted in northern Italy, in the Central Italian Alps (Pelfini et al., 2019). Several activities have been proposed such as the practice of geoclimbing on the field and the use of multimedia tools to get to know better geological concepts that normally can be less interesting for the students. The results show an improvement in the students’ knowledge, enhancing the idea that these activities really help scholars to better understand and memorize difficult but important notions (Bollati et al., 2018; Pelfini et al., 2019). Moreover, in 2020 a board game was prepared as an additional part. This choice derives from some studies that show how the use of board games in teaching has many advantages in engaging and motivating to learn in a new and unusual way for students, enabling students to apply critical thinking skills and to learn the scientific concepts. The proposed game is represented by a four-sided pyramid-shaped board (which recalls a mountain) with 15 cells for each side from the bottom to the top. The players are divided into 4 teams that try to win getting to the top as fast as possible answering correctly to some questions about geological, geomorphological and climbing concepts. According to the results obtained by testing it, the board game and the whole geoclimbing project are expected to provide social benefits to local communities, hopefully becoming part of the school programme.

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## **Student orientation under COVID-19 conditions: an example of online dynamic Earth Sciences Labs presentation**

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*Keywords:* Earth Sciences, student orientation, school student engagement

Over the past three decades, the online setting in high school student education and orientation programs has increased, becoming widely adopted during and after the COVID-19 block. Regarding student orientation, the University's websites now offer easy access to study programs, facilitate exploration of course structures and subjects, and provide extensive information on admission assessment, fees, location of laboratories and classrooms (Miller & Pope, 2003). However, this information does not engage students in experiences that enhance their knowledge, motivations and choices. These issues are crucial to remedy the problem of student retention and to favour the correct selection of the academic career (Bolliger & Martin, 2018; Groccia, 2018). Concerning the involvement of students, we present here an orientation experience carried out in February 2021 by the Department of Earth, Environment and Resources Sciences at the University of Naples Federico II (Naples, Italy), in order to promote the degree in Geological Sciences. The proposed event, aimed at high school students, was developed in an online environment using various technical and communicative expedients: dynamic presentation schemes, massive participation of university staff, young speakers, geology students with basic communication skills, direct contact with school students and description of the social or environmental effects in relation to geo-scientific disciplines. In addition, several key actions were carried out both in the preparation phase of the event, such as writing the texts of the speakers and rehearsing the storytelling related to the laboratories (labs) presentation, and during the orientation meeting. In relation to the latter issue, the dynamic face-to-face interaction has been achieved restricting in five-minute intervals the labs presentation, activating dialogue between speakers and changing webcam capture views. Finally, this work not only revisits the orientation strategy by describing the scientific, digital and communication tasks aimed at the high school student engagement, but also shows the benefits of training a scientific communication course for the staff involved in such an event.

Bolliger D.U. & Martin F. (2018) - Instructor and student perceptions of online student engagement strategies. *Distance Education*, 39(4), 568-583.

Groccia J.E. (2018) - What is student engagement? *New Directions for Teaching and Learning*, 154, 11-20.

Miller M.T. & Pope M.L. (2003) - Integrating technology into new student orientation programs at community colleges. *Community College Journal of Research and Practice*, 27, 15-23.

## **Che mostra! Un angolo di geologia nel nostro liceo**

Banfi A. & Veronesi P.\*

Liceo “GB Grassi” di Saronno.

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*Keywords:* didattica, minerali, PLS, PCTO.

Presso il laboratorio scolastico del Liceo “GB Grassi” di Saronno giaceva da tempo immemorabile, in un armadio di metallo, una raccolta di minerali e rocce, che ogni anno ci si riprometteva di ordinare e sistemare per un utilizzo didattico più efficace. Ma come fare? Durante l’anno il tempo è poco e a fine anno ci sono gli esami, i progetti da terminare, i documenti da consegnare e soprattutto... chi di noi, quasi tutte laureate in campo scientifico biologico, avrebbe avuto il coraggio di metter mano a tale impresa con il rischio di classificare un carbonato al posto di un silicato?

Grazie all’impegno delle autrici del poster e all’opportunità concessaci dal Dipartimento di Scienze della Terra “Ardito Desio” dell’Università Statale di Milano, la soluzione è stata trovata. Nel corso dello svolgimento del progetto afferente al PLS Geologia, intitolato “Che Mostra! Crea nel tuo liceo un angolo geologico”, gli esperti geologi, nelle figure del prof. Marco Merlini e del dott. Davide Comboni, hanno guidato un team di circa venti studenti, volontari e appassionati, alla realizzazione del nuovo catalogo digitale e soprattutto alla identificazione di tutti i campioni della collezione, compresi i più complessi! E’ stata inoltre un’occasione per insegnare ai giovani la storia e l’attualità dei minerali che passavano loro tra le mani, aspetto purtroppo spesso trascurato nella didattica di questa materia. Il risultato del lavoro è esposto ora nell’atrio della scuola, godibile e fruibile da tutti gli studenti e da tutti i visitatori del nostro Istituto.

## TURN On your smartphone and go

Conte G.<sup>1</sup>, Bilotta A.<sup>2</sup>, De Caterini G.\*<sup>3</sup> & Leoni G.<sup>4</sup>

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Keywords: GIS, discover, the teaching of geology, digital skills.

This project is the result of several years of debates and voluntary collaboration among teachers of different schools and geologists ( researchers and freelances).

Our leading idea comes from the words of Ardito Desio: "Every geologist is an explorer in his own home". We have a double aim to reach: we want to engage pupils and students with the discovery of their own territory and present a programme of computational thinking and technical skills using GIS (Geographic Instrument System).

The digital revolution we are leaving nowadays has basically changed the way to get, manage and use the data.

As a matter of fact modern data banks are geo-localized: while you surf the net looking for something you can also get information about where that place is. ( i.e. where that address is, where that monument is, a hiking trail).

The idea of re-discovery is the basis of scientific re-search which is based on the constant need every researcher of all times has always had, that is to look at the world from different viewpoints and with different diagnostic tools. Modern exploration, scientific research and the world of work have become a cross-disciplinary and shared experience driven by curiosity and technical expertise.

Ardea represents a complex social reality set in an ancient and amazing territory from a geological point of view, not only for its sites but also for its georesources and its environmental issues (natural and non natural). The title of this abstract is a play on words, the word "turn" recalls Turno, the king of Rutuli ( he was a character in the famous epic Eneide set in Ardea) and of course together with the word "on" they link the place together with the project.

Google Earth has been used as a tool together with a geographical app which enables you to put additional information such as the drawing of the area, routes, dots you can relate to more information, photos, pictures, etc. All information is displayed by the programme and can be shared with other people.

This project has been developed within the PON/FSE "Pensiero Logico Computazionale e della Creatività Digitale e delle Competenze di Cittadinanza Digitale", code 10.2.2A. All the classes were held in the computer lab where pupils had the chance to use some softwares, afterwards they did some activities to refer, from a geological p.o.v , to all the sites.

We made different small groups: Geology, Archeology, Environment, Alternative mobility. Teachers and pupils walked around the routes practicing and experiencing Google Earth.1

Desio A. (2005) - Sulle vie della sete dei ghiacci e dell'oro. L'autobiografia di uno dei più celebri esploratori italiani. Ed. Mursia (EAN: 9788842534402).

## The ‘Adopt a beach at a distance’ project

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*Keywords:* Citizen science, Marine Litter, virtual survey, aerial drone monitoring, environmental education.

This project aims to make students understand what the problem of marine litter (anthropogenic waste dispersed in the sea) is, and what the possible environmental consequences, thanks to their direct involvement in the analysis of data acquired on our beaches, using aerial drones. The images are real, acquired during the monitoring campaigns carried out by the Institute of Clinical Physiology of the CNR, in collaboration with the Institute of Marine Science and the Institute of Bioeconomy, both CNR, and the National Institute of Geophysics and Volcanology (INGV).

By analyzing aerial images of the monitored beaches, students collect useful information for research on the quantity, type, and spatial/temporal distribution of anthropogenic objects. This activity, designed to replace the classic manual monitoring on site that, this year, were impossible to carry out due to the COVID emergency, offered students the opportunity to familiarize themselves with tools for managing geographical data, such as QGIS, which are essential for the spatial analysis of information such as that produced by drones.

Following introductory lectures on the topic addressed, on the use of drones for environmental monitoring also supported by audio-visual material, students were instructed in the use of the functions necessary to perform data collection on photos using QGIS. At the end of the course, students reported some of the data collected by means of short and simple PowerPoint presentations, together with their consideration about this experience.

The project, being a didactic and educational experience, goes beyond the collection of data and the use of tools and protocols used in scientific research and aims to expand the knowledge of this serious problem by the new generations, and to predispose them towards more virtuous behaviors that include a reduction in the use of plastic, a better strategy for its disposal, the search for substitutive materials both compostable and biodegradable, and the move towards an economy that provides for recycling as a predominant action and that leads to a real decrease in pollution of our environment and our seas. To this end, it was provided, within the project, also an assessment of how many and what changes in knowledge and attitude have occurred in the students involved, through the administration of a short questionnaire pre and post activity. Results of this assessment will be presented in the communication.

The “Adopt a beach” educational path, which involved in 2021 up to 11 secondary school classes of 6 different scholastic institutions, have been ideated by the involved researchers after their attending, as experts, to the “course for teachers” held by the Museum of the University of Pisa in September 2020, as well as in connection with the exhibition “La Plastica e Noi” (Plastic and Us) held in the same museum from July 2020 to May 2021.



## Mapfly: a new research and teaching model on the cartographic heritage of the University of Padova

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Keywords: maps, GIS.

The University of Padova claims an impressive cartographic heritage, dated from 1668 to the present day, distributed in various Libraries and Departments and not yet known as it deserves. In particular, the Geography and Geosciences Libraries preserve over 40,000 maps of various types, from topographic and geographical maps to geological, geothematic and historical maps.

Thanks to the “Mapfly” project, funded by “Infrastrutture Immateriali di Ricerca” (Intangible Research Infrastructures), this cartographic heritage, now difficult to access, will be available to the public (autumn 2021) through the creation of a WebGIS portal. The portal will allow, by searching the basemap, to verify the presence in the catalog of maps of the area of interest and, with regard to the historical cartography in the public domain, also view the georeferenced digital reproduction on the web and proceed with the download of the same in the form of a file (GeoTIF), to be used locally on user’s GIS device. The new Web App will be previewed at the congress.

The Mapfly project has been carried out by the University of Padova and started in November 2020.

The portal has been developed according to the model of prestigious international agencies, in particular this one: <http://historicalmaps.arcgis.com/usgs/>, and involved transversal skills: three expert GIS technicians for georeferencing, to set up an additional Web App for data entry and for the development of the web interface, students who collaborated for the description of the encumbrance polygons of the cartography, and librarians that helped with cataloging, the analysis of descriptive metadata and to organize links to both the catalog and the University repository of digital collections. A technological partner supported the development of the Web App and its installation on the server. The acquisition of the digital maps has been carried out on a scanner developed for this service.

The study of geosciences will therefore be able to rely on a tool for research and analysis of cartographic documentation that is easy to access and potentially of great interest for research, degree theses and practical classes.

The Web App will make it possible to enhance and make fully usable the extraordinary cartographic resources of the University, that are so far difficult to consult and search through traditional catalogs. In fact, thanks to the WebApp it will be possible to get to know the availability of all the cartographic heritage of the area of interest, filter it by type of map or on the basis of a time period, and (as far as a digital copy is available) proceed with the diachronic study of a territory using the techniques of representations (transparencies) offered by the App or by downloading and superimposing the cartography of interest on GIS. The latter techniques appear to be particularly effective for applications in the fields of geomorphology and landscape study.

Cefis M. (2016) - La cartoteca della biblioteca di Geoscienze di Padova nell’era digitale. Tesi magistrale in Storia e gestione del patrimonio archivistico e bibliografico, presso l’Università Cà Foscari di Venezia. <http://tesi.cab.unipd.it/53461/>.

Allord G.J., Walter J.L., Fishburn K.A. & Shea G.A. (2014) - Specification for the U.S. Geological Survey Historical Topographic Map Collection. U.S. Geological Survey Techniques and Methods, book 6, chap. B11 <https://dx.doi.org/10.3133/tm11B6>.

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Lucilia G. (2011) - Interpretazione e confronto tra cartografie storiche, topografiche e immagini analogiche in “chiave geologico-geomorfologica”. Bollettino A.I.C., 143, 53-72. <https://core.ac.uk/download/pdf/41179534.pdf>.

**S29.**  
**Open Poster Session**

## The hadrosaur and nodosaur ichnoassemblage from the Altamura dinosaur tracksite (early Campanian; Apulia, southern Italy)

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Keywords: ornithopods, ankylosaurs, close-range photogrammetry, palaeobiogeography.

The ichnological survey of the track-bearing surface in the Pontrelli quarry (Altamura, Apulia) was performed using both traditional and new methodologies. Approximately 26,000 footprints were identified, 600 of which arranged in 12 quadrupedal trackways. Close-range photogrammetry was applied to gain accurate 3D models of the best-preserved specimens. The ichnological study, supported by morphometric analysis and photogrammetric models, led to the identification of different morphotypes, produced by two dinosaur trackmakers. In the Morphotype 1 are included the specimens characterised by tridactyl pes, which digits are lobe-shaped, and smaller manus (i.e., heteropody index between 1:5 and 1:2) with three subcircular pads. This ichnotaxonomical group includes the ichnospecies *Apulosauripus federicianus*, established by Nicosia et al. (2000) to describe the trackway ACDL99/3. Nevertheless, numerous footprints can be also morphologically matched to the ichnogenus *Caririchnium* Leonardi, 1984. Six trackways can be assigned to this morphotype, including the two longest trackways of the ichnosite (represented by 75 and 88 manus-pes couples). The specimens of Morphotype 1 are referred to ornithopod dinosaurs, likely to medium-sized hadrosaurs with a hip height between 74 and 125 cm and up to 4.5 m long. The closest candidate is to date *Tethyshadros insularis*, 4-5 m long hadrosauroid from the upper Campanian-lower Maastrichtian deposits of Villaggio del Pescatore (Trieste, NE Italy). The Morphotype 2 is represented by a broad tetradactyl pes and a slightly smaller manus (i.e., heteropody index between 1:3 and 1:2 on average, in some specimens up to 1:1), in which four or five digits are barely recognizable. Six trackways are referable to this morphotype, among which the longest is constituted by 39 quadrupedal steps. The morphological features of these tracks closely match those of the ichnogenus *Tetrapodosaurus* Sternberg, 1932, typically attributed to ankylosaurs. According primarily to the medium size of the ankylosaurian trackmaker of Altamura (hip height = 60-92 cm, body length = 2.5-4.5 m), the coincidence correlation method (Carrano & Wilson, 2001) suggests a nodosaurid as most suitable candidate, similar to the 2.5 m long *Struthiosaurus* or the 4 m long *Hungarosaurus* from the Santonian-Maastrichtian deposits of Europe. The occurrence of these two dinosaur groups in the Late Cretaceous of the Apulian Carbonate Platform can represent the keystone to enhance the knowledge on the palaeogeographic framework of the Periadriatic region.

Carrano M.T. & Wilson J.A. (2001) - Taxon distributions and the tetrapod track record. *Paleobiology*, 27(3), 564-582.

Nicosia U., Marino M., Mariotti N., Muraro C., Panigutti S., Petti F.M. & Sacchi E. (2000) - The Late Cretaceous dinosaur tracksite near Altamura (Bari, southern Italy). II - *Apulosauripus federicianus* new ichnogen. and new ichnosp. *Geologica Romana*, 35(1999): 237-247.

## **Fibrous antigorite veins in Liguria and Calabria serpentinites: a preliminary assessment for NOA risk evaluation**

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*Keywords:* serpentinites, fibrous antigorite, naturally occurring asbestos (NOA).

The presence of naturally occurring asbestos (NOA) in rocks and soils represents a potential risk to human health. In recent years, several fibrous minerals other than the six regulated asbestos have been recognized to be potentially toxic to human health. In the serpentine group, fibrous antigorite is receiving increasing attention due to its wider occurrence in meta-ophiolite contexts. Fibrous antigorite toxicity is currently under evaluation and researchers have raised concern about its possible health effects. Fibrous antigorite veins are widespread in the antigorite serpentinites of Liguria (Voltri and Palmaro-Caffarella Units, Voltri Group) and Calabria (Gimigliano-Monte Reventino Unit, Southern Ligurian Domain). These occurrences were investigated as part of a research project for the assessment of the risk related to non-regulated fibrous minerals naturally occurring in Italy. In the selected outcrops, fibrous antigorite is found in veins up to several cm thick, commonly polyphase, showing either cross- or slip-type fibre arrangement. Fibrous antigorite is commonly associated with opaque minerals (magnetite + hematite) and chrysotile, the latter developed during reactivation of the antigorite veins. Fibrous antigorite veins are commonly associated with veins with fibro-lamellar or lamellar habit antigorite, showing very similar petrographic features. Distinction among the different antigorite morphologies was made by SEM morphological evaluation of the mineral particles released by grinding of the vein material.

## **Compositional and geometrical features in ore deposits: A comparison between karst bauxite deposits**

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*Keywords:* karst bauxites, geochemistry, image analysis, fractal dimension, aggregation process.

The interest for the study of karst bauxite deposits has dramatically increased recently since these deposits are frequently enriched in valuable elements of major economic importance (Abedini and Calagari, 2015; Herrington, 2013; Mongelli et al., 2017) and furthermore they provide useful information regarding the paleo-conditions during their formation (Boni et al., 2012; Mindszenty et al., 1995; Mondillo et al., 2011; Mongelli et al., 2016). The texture of karst bauxites may be “ooidic” when composed of sub circular concretions (ooids), dispersed in a fine matrix (Bardossy, 1982). These sub-spherical concretions show a concentric structure with different composition that testifies an alternation of different climatic conditions during their formation (Mongelli et al., 2015). Fractal geometry represents a valuable approach for analyze several range of structures ranging from molecules and atoms to the coastlines of continents (Meakin and Fowler, 1995). Meakin (1991) observed the aggregation of small particles to form larger structures are important in several natural processes. Buccione et al. (2016) stated that the formation of minerals can be described in terms of fractal geometry performing image analysis on textural components of Southern Italy bauxite samples, which provide geometric parameters of the ooids (circularity, aspect ratio and fractal dimension). In particular, fractal dimension is quite interesting since the growth of sub-spherical concretions, such as ooids within karst bauxites, can be considered as the growth of fractal aggregates. Fractal dimension (D) for the Salento autochthonous bauxite pebbles, for instance, is very close to D values related with diffusion-limited aggregation models while Campania bauxites exhibited higher Fractal Dimension values which are close to the fractal dimension associated to the diffusion-limited cluster aggregation processes where small particles join together to form further clusters that continue to keep on join to form larger and larger clusters (Meakin, 1991; Mongelli et al., 2016). The shape, the number and composition of these aggregates is strongly dependent on climatic conditions and so the study of these parameters in bauxite deposits of different localities can provide information regarding the climatic and environmental conditions at the time of their formation. In this work, image analysis results carried out on some Mediterranean type karst bauxite deposits on which, image analysis, has never been performed.

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## Use of alternative methodologies useful for identifying relict sands on the continental shelf, in order to nourish eroded beaches

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*Keywords:* relict sand, beach nourishment, continental shelf, sediment flux.

Strong anthropogenic pressure and the increasing realization of coastal defence works and harbours, have greatly increased the erosive phenomena of the Italian coasts. It is therefore essential improve the coastal defence techniques supported by a preventive technical and environmental analysis, followed by a careful monitoring program. Among these, beach nourishment consists in introducing, along the beach affected by erosion, sediments with grain size and composition compatible with the existing one.

The identification of substantial quantities of relict sands is currently a costly and time-consuming process. It is therefore necessary to develop alternative methods, which have low impact on the environment and that allow a reduction of execution times and costs. This research is aimed at studying sediment flux, useful to predict the volume, timing and location of the sediments that are transported from an erosional source region into a depositional accumulation basin. This approach could lead to the identification of areas on the continental shelf where the probability to discover relict sand deposits is higher.

In this study, two widely used models to estimate sediment flux are applied: the BQART model (Syvitski and Milliman, 2007) for the estimation of suspended load, and fulcrum model (Holbrook and Wanas, 2014) for the estimation of the bedload. These methodologies have been applied to the catchment areas of the Milicia and San Leonardo rivers (north-western Sicily), since relict sand deposits have been identified in the Termini Imerese offshore at a depth of about 120 m and a volume of  $130 \times 10^6$  m<sup>3</sup>. The aim is to verify whether the sediment flux calculated with the 2 methods is compatible with the amount of sands that have been deposited on the continental shelf during the sea-level lowstand, ranging from 23 to 18 thousand years ago .

The obtained values, calculated over an interval of ~ 5000 years (sea-level lowstand interval), provide a total volume of ~  $30 \times 10^6$  m<sup>3</sup>, lower than the relict sands volume located in the Termini Imerese offshore. This result, indicates that sedimentary volumes linked to external forcing, such as Longshore Sediment Transport Rate (LSTR), must be taken into account in the total calculation. For the determination of the LSTR it was decided to use the CERC formula (Shore Protection Manual, 1984) since it is the only one for which all the fundamental parameters for the calculation are available.

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## **The role of post-orogenic normal faulting in hydrocarbon migration in fold-and-thrust belts: insights from the Latina Valley (central Apennines, Italy)**

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*Keywords:* Central Apennines, hydrocarbon migration, bitumen outcrops, Ripi oil field.

In the Latina Valley (Central Apennines, Italy) several discontinuous bitumen outcrops and a well-known oil field occur, cultivated since the 19th century. The distribution of such deposits is strongly controlled by faults, which have a fundamental role in controlling hydrocarbon migration, entrapment, and/or leakage within fold-and thrust belts. However, little attention has been dedicated in the past to the role of post-orogenic normal faults in controlling hydrocarbon migration during the orogenic collapse. Field and subsurface data are here combined with geological evidence from the Ripi oil field, and a conceptual model is proposed for hydrocarbon migration along post-orogenic normal faults and entrapment within shallow reservoirs. Results show that post-orogenic normal faults promoted updip hydrocarbon migration from Upper Triassic mature source rocks, which generated oil during foreland/foredeep flexure and subsequent involvement into the accretionary wedge. Where pre-orogenic deposits were covered by less-permeable syn-orogenic sandstones, marls, and clays, hydrocarbons moved laterally from normal faults and impregnated high-porosity sandstone lenses, generating discontinuous and heavy oil reservoirs. On the contrary, where syn-orogenic deposits were eroded in response to orogenic uplift, hydrocarbons leaked at the Earth's surface. Results from this study can be applied to reduce risks during hydrocarbon exploration and appraisal in similar tectonic settings.



## Upper Jurassic coral assemblage from condensed pelagic deposits of the Umbria-Marche Apennines (central Italy)

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*Keywords:* Apennines, Kimmeridgian, Tithonian, coral, Pelagic Carbonate Platforms.

We report a new coral assemblage collected from Kimmeridgian–Tithonian pelagic deposits of Northern Apennines. Such corals proliferate on intrabasinal structural highs (Pelagic Carbonate Platforms - PCPs) originated from dismembering and drowning of the vast Calcare Massiccio carbonate platform during the Early Jurassic Western Tethys rifting stage. The drowning was followed by condensed pelagic sedimentation on the top of PCPs. Both zooxanthellate and azooxanthellate corals have been found in these facies. The occurrence of zooxanthellate corals in PCP-top condensed successions allowed to constrain the bathymetry of these depositional systems to the photic zone (40 – 150 m).

The here studied material is represented by solitary, probably azooxanthellate corals, associated with light dependent organisms, such as pennular corals. The specimens usually display elliptical to circular calices and have ceratoid attached morphologies, finely granulated costosepta with a clear crown of palis. These features allow the possible assignation to the scleractinian extant family Caryophyllidae. The collected azooxanthellate fauna is oligotypic but abundant, as a possible result of very slow sedimentation rates and extreme condensation. Most of the corals do not display in-life position, being detached from the substrate and randomly arranged within the pelagic deposits; others grew on ammonites shells or on other corals. The new occurrence improves the Late Jurassic record of caryophyllids, providing additional constraints on their paleoecology and on the paleoenvironmental evolution of this sector of Western Tethys.

## Analogue models of Rift-Rift-Rift triple junctions

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*Keywords:* triple junction, continental break-up, analogue models, Afar depression.

Continental break-up at Rift-Rift-Rift triple junctions represents the “prequel” of oceanic basin formation. Currently, the only directly observable example of a Rift-Rift-Rift setting is the Afar triple junction, where the African, Arabian and Somalian plates interact to form three rift branches, two of which are experiencing oceanization (the Gulf of Aden and the Red Sea) and the younger of the three (the Main Ethiopian Rift) is still in the continental break-up phase.

To study continent break-up processes, we performed two experimental series (Series 1 and 2) of analogue models simulating continental rifting in a Rift-Rift-Rift triple junction to investigate the resulting structural pattern and evolution. In Series 1, starting from a theoretical triple junction (three branches at 120° experiencing orthogonal extension) we adopted a parametrical approach, modifying the ratio of plate velocity between the plates and performing single-phase (all the three plates move) and two-phase models (with a first phase where only one plate moves and a second phase where all the three plates move). In a second series (Series 2) the direction of extension was changed to induce orthogonal extension only in one of the three rift branches. Our single-phase models suggest that differential extension velocities in the rift branches affect the localization of the triple junction, which is located closer to the rift branch experiencing slower extension velocities. Furthermore, differential velocities affect strain partitioning along faults: the effect of a faster plate is to favour the formation of structures trending orthogonal to dominant velocity vectors, while faults associated with the movement of the slower plates remain subordinate. In contrast, similar velocities lead to the formation of a symmetric fault pattern at the triple junction, where strain partitioning is balanced between the three rift branches. Two-phase models reveal high-angle faults interacting at the triple junction and confirm that differential extension velocities in the three rift branches strongly affect the fault pattern development. Models performed in Series 2 whose setting better apply to the Afar triple junction, in fact provide large scales similarities with the fault pattern observed in nature, where dominant ~W-E faults and subordinate crosscutting ~NW-SE fault likely developed in two phases of extension under differential velocity conditions.

## Circulation of sulfate-rich fluids along extensional faults in the Apennines: an example from the Gubbio normal fault

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*Keywords:* fluid-rock interaction, faults, carbonate rocks.

Fluids such as aqueous solutions, hydrocarbons and/or gases (e.g., H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>S) flow within the Earth's crust controlled by porosity and fracture systems of rocks. Fluids in chemical disequilibrium with the mineral assemblage of the host rock may induce dissolution of pristine minerals and precipitation of authigenic minerals thus generating intense alteration of the chemical and physical properties of the host rocks such as rock bleaching. The study of fluid-rock interaction in faults provides information on paleofluid circulation along fault zones and fluid origin.

Bleaching of red pelagic limestones of the Northern-Central Apennines has been frequently explained as a variation of the redox state conditions of the seafloor during carbonate deposition. Despite this primary non-coloration, secondary bleaching of red carbonates in association with faults has been extensively observed in the Umbria-Marche Apennines. In particular, bleaching of the red pelagic carbonates (Late Cretaceous-Eocene Scaglia Rossa Fm.) has been observed along the Gubbio normal fault, an active SW-dipping fault, antithetic to the Altotiberina ENE-dipping low-angle detachment.

The Gubbio fault cuts through the Gubbio anticline and, at the surface, juxtaposes Quaternary deposits in the hanging-wall with Jurassic-Oligocene carbonates in the foot-wall. At depth it cuts through the Triassic Burano evaporites and terminates against the Alto Tiberina Fault. In the Scaglia Rossa Fm., secondary bleaching occurs as 10-15 cm wide alteration haloes across conjugate hybrid fractures with strike-slip kinematics, filled by blocky calcite. Optical petrography shows that bleaching extent is controlled by pattern of microfractures and reactivation of pre-existing stylolitic seams. SEM, XRD and LA-ICP-MS analyses along and across the alteration haloes show that hematite is completely dissolved, and iron is remobilized by the fluid. In addition, the alteration front is marked by the occurrence of euhedral crystals of baryte in micritic voids and along stylolitic seams.

These observations allow us to conclude that bleaching is yield by the interaction between the carbonate host rock and ascending H<sub>2</sub>S-CO<sub>2</sub>-rich fluids, likely derived from sulfate reduction of the deep-seated Burano evaporites, which mixes with shallow groundwaters. The complex fault architecture of the Gubbio Fault thus enables the rising of deep fluids along minor fractures in the damage zone, which cause local element mobility and precipitation of new mineral phases.

## **Pre- vs. syn-folding fracturing: insights from field and virtual structural analyses along the Pietrasecca anticline (central Apennines)**

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*Keywords:* folding, fracturing, central Apennines, foredeep.

Understanding the timing of fracturing on anticlines is crucial to model fluid circulation within structural traps. Fracture orientations and distributions have been extensively analyzed on exhumed anticlines in order to understand their relationship with the folding process. Anticlines from fold and thrust belts worldwide are commonly characterized by joints striking parallel (longitudinal joints) and perpendicular (transversal joints) to the fold axis, which have been usually attributed to folding-related processes. However, other studies conducted on undeformed forelands demonstrate that fractures striking parallel and/or orthogonal to the trench-forebulge trend form in the foreland region prior to thrusting and folding.

Here we use the Pietrasecca anticline, in the central Apennines, as a case study to show how a detailed field structural analysis can shed light on the origin of fracturing and faulting on anticlines. The study area is characterized by Lower Cretaceous and middle Miocene shallow-water limestones, passing upwards to foreland and foredeep deposits (i.e., Orbulina Marls and siliciclastic turbidites). The stratigraphic succession is involved in a thrust-related and NE verging anticline, which is cut by WSW-ENE striking and SSE dipping high-angle normal faults.

Scanlines and field observations on cross-cutting relationships, coupled with a virtual outcrop model, show that the longitudinal and transversal joint sets affecting the anticline are characterized by (1) being orthogonal to bedding, (2) orientations that locally deviate from the directions parallel and orthogonal to the fold axis, (3) intensity and orientation unrelated to the structural position on the anticline and to the different stratigraphic units. The intensity of the transversal joint set abruptly increases nearby the normal faults. In addition, tectonic pressure solution cleavages affecting middle Miocene limestones form a constant angle with bedding and frequently abut against both joint sets.

Our results demonstrate that joints, and possibly an embryonic version of the WSW-ENE striking normal faults, formed in a foredeep tectonic environment, before the development of the pressure solution cleavages. We underline that the orientation of the joint sets with respect to the orientation of the axis of the anticline is not sufficient to attribute the joint origin to the folding process. Detailed structural studies are thus necessary to better constrain the pre-folding vs. syn-folding nature of joints.

## Seismically-induced landslide estimation at regional scale in El Salvador volcanic territory

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**Keywords:** earthquake-induced landslides, CASTES project, seismic microzonation, El Salvador seismicity, natural hazards.

The estimation of landslide hazard triggered by seismic events has been studied since 1965 through Newmark’s studied (Newmark, 1965). From the beginning up today, the mechanical approach to slope instability has been extended to GIS-based methods which are enable to consider the spatially distributed geomorphological and seismological variables strictly related this type of instabilities. Both predisposing and triggering variables are commonly combined by different methods (i.e. data driven, geostatistical, machine learning) to create maps at regional and urban scale. This latter scale is currently used worldwide for developing seismic microzonation of slope instabilities affecting urban areas threatened by high-magnitude earthquakes in several different geological contexts. In the American continent, USGS collected in continuously updated web-GIS database informations about earthquake-induced landslides. It is the case of El Salvador, located in Central America, where the complex geodynamic is characterized by the interaction of four major tectonic plates and several microplates on their boundaries that cause high-magnitude seismic phenomena. Additionally, the lithostratigraphic and geomorphological characters (i.e. acid pyroclastites, volcanic ashes and pomices), are commonly affected by heavy rainfalls, so that hundreds of landslides are generated and consequently a huge number of casualties and economic losses. In this country, the Italian Agency for Development Cooperation (AICS) funded the CASTES project, which is devoted, among the numerous objectives of this international collaboration programme, to study unstable co-seismic effects induced within El Salvador territory. To this aim, a preliminary approach to define landslides hazard induced by the 2001 earthquake sequence has been applied. This latter consists of detecting the seismically-induced landslide inventory from aerial obtained after the two main shocks occurred on 13 January and 13 February 2001 (Mw 7.7 and 6.6, respectively). Then, the two magnitudes and landslides epicentral distances have been compared with the Keefer’s and Martino’s landslide triggering thresholds (Martino et al., 2014). These curves are useful in microzonation activities to estimate the possible occurrence of earthquake-induced landslides both in soils and rock formations related to all kind of kinematics. Nonetheless, according to the present authors’ knowledge, these curves have not been calibrated through volcanic geological territories, yet. Hence, this contribution is aimed at investigating the peculiar characters of the seismically-induced landslides in volcanic territories and to compare their triggering threshold to those ones identified worldwide.

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## Living along a Pliocene Tuscan coast: terrestrial, freshwater and marine vertebrates from La Serra quarry (Tuscany)

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*Keywords:* Pliocene, fishes, mammals, Tuscany, palaeoecology.

For centuries, the Plio-Pleistocene deposits of Tuscany (central Italy) have been the location of prime discoveries of fossil vertebrates. Though such finds have significantly contributed to international vertebrate palaeontology, many of these historical finds lack precise stratigraphic whereabouts; furthermore, correlations between continental and marine assemblages have always been difficult, thus hampering integrative palaeoecological reconstructions. Here, we provide a preliminary characterization of the vertebrate assemblage from La Serra quarry (Pisa Province, Tuscany), where the exposed Pliocene sediments are arranged into a transgressive-regressive cycle that testifies to coastal marshes, deltaic-estuarine environments, semi-protected lagoons and shoreface settings. The vertebrate assemblage from these deposits features some fifteen species of mammals, reptiles and fishes. Mammals are mostly represented by isolated remains referable both to juvenile and adult individuals of Proboscidae indet., a small-sized Cervinae, a large-sized Cervidae, and *Sus* cf. *S. arvernensis*. The proboscideans are represented by large-size vertebrae and ribs. Cervidae are documented by isolated teeth and some postcrania that resemble the late Ruscinian Cervinae. The suid is represented by a juvenile specimen, smaller than *Sus strozzii* and *Propotamochoerus provincialis*, and closer to the relatively small-size suid from the Baccinello V3 fauna. The fish remains include dental and dermal elements of *Carcharhinus* cf. *perezi*, *Carcharias taurus*, *Carcharodon carcharias*, *Galeocerdo cuvier*, *Myliobatis* sp., *Dasyatidae?* Indet. (including the longest tail spine ever reported from the fossil and Recent records), *Sparidae* indet., and *Tetraodontidae* indet. The turtles are represented by a cervical vertebra of *Chelonioidea* indet. as well as by plastral and carapacial elements of *Mauremys* sp. and *Testudo* sensu lato. By including terrestrial, freshwater, and marine forms, the vertebrate assemblage from La Serra represents an ideal scenario for providing a synoptic glimpse into a Pliocene paralic ecosystem of Tuscany, as well as for elaborating novel correlations between terrestrial, freshwater and marine vertebrate assemblages.

## Factors controlling the evolution of badlands in different northern apennine formations

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*Keywords:* badlands, Emilia Apennines (northern Italy), Ligurian formations.

Badlands are landforms of the relief of noteworthy landscape interest, typical of marly and clayey hillslopes, as well as ecological niches of significant environmental significance. They are characterized by a dense and hierarchical network drainage, with deep incisions, with little or no vegetation cover, and represent areas of active hydrogeological instability with a great intrinsic value, representing significant elements of the geological heritage. They are extremely widespread in the Emilia Apennines but little investigations were carried out to evaluate factors controlling their development. Among the factors suggested in the literature, those indicated as critical in the development, persistence and evolution of badlands are lithology, structural setting, attitude, physical, chemical and mineralogic properties of the rock, climatic factors, vegetation cover.

The Modena Apennines are widely affected by hillslope degradation, and several badland examples are present in the area along the Panaro River (Coratza and Parenti, 2021).

In the selected area, near Marano sul Panaro (Modena province) outcrop three different formations, belonging to two different paleogeographic domains: the Blue clays Formation (Argille Azzurre), which represents the marine deposition of the Intra-and Pede-Apenninic basin; the Varicolored clay-shale Formation (Argille varicolori) and the Palombini-shales Formation (Argille a Palombini), both belonging to the ligurian domain but very different in terms of lithology, being the former mainly argillaceous and the latter characterized by a widespread presence of calcareous blocks of different size floating in an argillaceous matrix (Gasperi et al., 2005). Furthermore, the ligurian formations underwent a much more severe tectonic stress with respect to the Argille Azzurre Formation.

In this study we investigate the inference of geological, sedimentological, morphological and mineralogical factors in the evolution of badland areas and the importance and role, if any, of each factor examined.

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## **Looking for active faults in a low strain rate region through a multidisciplinary land-to-sea approach: clues from the North-Western Sicily (southern Italy)**

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*Keywords:* active deformation, morphotectonic, low strain rate regions.

Low Strain Rate regions (LSRr) are areas deforming at a 1 mm/yr rate or less. Such regions are the most globally widespread areas and host significant cities and high-vulnerable anthropogenic assets. Infrequent but high-magnitude earthquakes proved that identifying active structures in the LSRr is one of the primary challenges that the scientific community and modern societies must face. Identifying these structures in the LSRr is hampered by the lack of valuable outcrop data due to the anthropogenic and climate overprinting of the faults morphological signature. We propose a multidisciplinary approach to detect active geological structures and their related deformation. We selected as a natural laboratory an LSRr located between two major cities of Sicily (southern Italy) to test this approach. The selected area lies into the northern sector of the Apennine-Maghrebian fold and thrust belt and its offshore prolongation. The proposed approach consists of quantitative morphotectonic, offshore and onshore tectonostratigraphic and GNSS joint analyses. The main achieved results are 1) the first evidence of active, shallow-sited, NNW-trending transpressive blind faults that extends partially offshore for about 30 km, which décollement levels located at about 3 and 1 km depth, respectively and their 3D model, 2) a morphotectonic evolution model, that represents where and how these geologic structures drove the landscape evolution of the study area. Finally, we highlight that only a multidisciplinary approach could help detect and parametrize active faults in slow deforming areas that cross the coastline physical limit.

## **New data from the Lower Cretaceous carbonate platform deposits of Dimitrovgrad section (Southeastern Serbia)**

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*Keywords:* Lower Cretaceous, facies analyses, limestones, Getic, Serbia, carbonate platform.

Lower Cretaceous carbonate platforms record distinctive facies in the area of Getic unit defined Beriasian, Valanginian, Hauterivian and Urgonian like facies. These deposits result from the continuous trend of shallow-water sedimentation that started in the Middle Jurassic time. Recent studies on the Getic carbonate platform succession focused on outcrops in Romania and Bulgaria, whereas detailed investigation on the Serbian side of the Getic platform was limited to solving biostratigraphy, paleontology and facies distribution issues on local scale, mostly in northeastern Serbia. The most exhaustive research on the Getic platform in southern and central Serbia dates back to the 70s of last century (Jankičević, 1978).

The study area is located in the Carpatho-Balkanides of Serbia, close to the town of Dimitrovgrad, and includes the narrow belt of Lower Cretaceous (Valanginian-Hauterivian) carbonate successions in the southern sector of the Getic Carbonate Platform. The identified carbonate facies consist of foraminifera mudstone to wackestone, bioclastic wackestone, (fenestral) peloidal grainstone, skeletal packstone and mixed siliciclastic sediments (sandstone) indicative of different environments from shallow platform interior to slope and basin. The data from Dimitrovgrad locality with beds fully made of *Bacinnella* sp. show the significant changes in environment of deposition from platform interior to reef depositional environment. Besides that, the pyrite rich siliciclastics provide the information of transition to slope environment.

The distribution of different facies show rapid lateral and vertical changes of depositional environments varying from platform interior to reef and finally to the slope and basin conditions.

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## **Regional stratigraphic correlation, palaeogeography and age insights on the Anisian successions of Sardinia through new and revised palynological analysis**

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*Keywords:* Anisian, palynology, Sardinia, Buntsandstein, biostratigraphy.

Due to the inception of a new tectonic cycle during the Late Permian - Middle Triassic transition, the W Europe experienced an important paleogeographic change that was mirrored in an alteration of climatic and environmental conditions in the Western Tethys domain. This led to the settling of adverse conditions that favoured successive and rapid ecological crises, mainly concentrated in the Early Triassic, with the consequent lack of paleontological records at the European level. In Sardinia in particular, the lack of paleontological record is accompanied by a stratigraphic gap that extends from the early Middle Permian to the Early Triassic p.p. Nevertheless, the study of the Triassic successions of this island offers important insights regarding the evolution of the southern margin of Paleo-Europe and the Western Tethys domain, as Sardinia occupied a key position in the European paleogeographic scenario. Our study focuses on new stratigraphical-sedimentological and palynological analysis of the Anisian sedimentary record of the island and on a detailed revision of all the papers regarding the Sardinian microfloral associations of this age. In particular, the Su Passu Malu section (Campumari, SW Sardinia), Arcu is Fronestas section and Escalaplano section (Escalaplano, Central Sardinia) have been studied in detail. In addition, regional correlations were made with other sections in the SW (Scivu Is Arenas) and NW (Nurra) of the Island. This study permitted to accurately ascribe the age of these successions and to obtain updated and more precise insights regarding the timings of the transgression in the Western Peri-Tethys domain. These data also allow obtaining a more precise paleogeographic reconstruction of Sardinia during the Anisian.

## Study of the origin, the evolution, and the distribution of Monte Amiata mafic enclaves

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*Keywords:* Monte Amiata, enclaves, petrography, chemical analyses, statistical survey.

The Monte Amiata volcano is located in southern Tuscany, at the geographical overlap of the Tuscan magmatic province with the Roman magmatic province. It is a small Pleistocenic volcano made up prevalently by viscous lava flows and domes ranging in composition from trachydacites to olivine latites. The volcanic rocks emplaced in a very short period of time, between 305 and 231 ka (Laurenzi et al., 2015). Lava flows and domes are grouped into three main complexes, one for each stage of activity: the “Basal Trachydacitic Complex” (BTC), the “Dome and Lava flow Complex” (DLC) and the “Olivine Latite final lavas” (OLF; Conticelli et al., 2015; Marroni et al., 2015).

The most important petrographic characteristics of Monte Amiata volcanic rocks are represented by: i) the occurrence of sanidine megacrysts, mostly confined in the rocks emplaced in concomitance with the second stage of the Monte Amiata volcanic activity (DLC); ii) the occurrence of rounded fine-grained mafic enclaves with cuspidate margins convex toward the host, which constitute proof of the mingling process that took place at Monte Amiata and that possibly triggered the eruptions of these highly viscous magmas; iii) the occurrence of mafic olivine latitic lava flows, emplaced as the final product of the volcanic activity and characterised by an intermediate composition between the early silica-rich volcanic rocks and the most mafic enclaves hosted by Monte Amiata volcanic rocks.

Here, we present the preliminary results about the origin, the evolution, and the distribution of the mafic enclaves hosted by the Monte Amiata lavas and domes. To do this, thin sections were studied under the petrographic microscope, chemical analyses of whole rocks and enclaves and their rock-forming minerals were carried out. A statistical survey on the magmatic enclaves distribution and their size variations was also made. These preliminary results suggest that Monte Amiata mafic enclaves change in composition and increase in size and abundance from those hosted by domes and lavas with the highest silica contents to those hosted by domes and lavas with the lowest silica contents.

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Laurenzi M.A., Braschi E., Casalini M., Conticelli S. (2015) - New <sup>40</sup>Ar-<sup>39</sup>Ar dating and revision of the geochronology of the Monte Amiata Volcano, Central Italy. *Ital. J. Geosci.*, 134, 255-265.

Marroni M., Moratti G., Costantini A., Conticelli S., Benvenuti M.G., Pandolfi L., Bonini M., Cornamusini G. & Laurenzi M.A. (2015) - Geology of the Monte Amiata region, Southern Tuscany, Central Italy. *Ital. J. Geosci.*, 134, 171-199.

## Late Albian ammonites from Kotraž (Topola area, Central Serbia) and their biostratigraphic implications

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Keywords: Upper Albian, ammonites, biostratigraphy, Kotraž, Central Serbia.

The Early Cretaceous ammonite fauna is well-known from several localities in Central Serbia. Discovered Lower Cretaceous sediments extend in the narrow belt Belgrade-Kosmaj-Topola-Gledić Mts. (Anđelković, 1954). The wide study area belongs to the: Eastern Vardar Ophiolitic Unit (Schmid et al., 2008), Main Vardar Zone (Karamata, 2006) or Northern part of Central Vardar Subzone (Dimitrijević, 1997). Newly collected ammonite assemblages described herein came from Kotraž section located SW of Topola in Šumadija District. In Serbian geological literature, the oldest Cretaceous sediments of this area are described as Barremian-Aptian shallow-marine limestones, which are overlying younger Upper Albian glauconitic sandstones, marls and marly sandstones (Anđelković, 1954). The Upper Albian sediments of Kotraž section profile are represented by 11 m thick glauconitic sandstones and marly sandstones bearing rich fauna of ammonites, belemnites, gastropods and plant tissues. These sediments yielded a rich ammonite fauna that includes representatives of three superfamilies of Phylloceratoidea, Tetragonitoidea and Desmoceratoidea. The lower and middle part of the profile is dominated by 8 m thick glauconitic sandstones and reddish Fe-rich sandstones from which some ammonite taxa are isolated: *Anisoceras* sp., *Mortoniceras* sp., *Phylloceras* (*Hypophylloceras*) *velledae* and *Puzosia mayoriana*. The uppermost part of the profile, consists of 3 m thick sandy marls and marly sandstones with dominant fauna of genus *Puzosia* and other species: *Kossmatella agassiziana* and *Puzosia* (*Puzosia*) *mayoriana*. The studied deposits with ammonite assemblages belongs to the lower part of the *Mortoniceras perinflatum* Zone (sensu Reboulet et al., 2018).

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## Geothematic map and ichnological review of dinosaur tracks from the Lavini di Marco ichnosite (Early Jurassic, Southern Alps, NE Italy)

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**Keywords:** close-range photogrammetry, drones (UAVs), theropods, sauropodomorph, Trento carbonate Platform.

The Lavini di Marco ichnosite (Trentino-Alto Adige), discovered in 1989, is one of the most extensive European dinosaur tracksites, being the subject of several studies since early 90's. The track-bearing layers are referred to the Monte Zugna Fm. (Hettangian-lower Sinemurian) of the Calcari Grigi Group, settled down within the palaeogeographic domain of the Trento carbonate Platform. In 2018, a new field survey was performed, as part of a joint project between MUSE - Science Museum of Trento, Sapienza University of Rome and Autonomous Province of Trento. The goal was to carry out an ichnological review and to realize the first geothematic map of the whole tracksite. During the survey both traditional and innovative methods were used, such as aerial and close-range photogrammetry. More than 700 tridactyl tracks and about 200 quadrupedal tracks were detected, and we mapped 27 trackways of both bipedal and quadrupedal dinosaurs. Close-range photogrammetry allowed to gain detailed morphological information, thus refining the ichnotaxonomical assignment. Morphological and morphometrical analyses allowed to assign most of the tridactyl tracks to the ichnogenus *Kayentapus*, although some specimens can be referred to the ichnogenera *Anchisauripus*, *Grallator* and *Eubrontes*. The occurrence of ornithischian ichnotaxon *Anomoepus* (previously hypothesized on the basis of two sub-parallel elongated tracks) was denied by the photogrammetric model, revealing the overlap of two tridactyl footprints with different size. The ichnotaxonomical review of quadrupedal trackways led to the emanation of the diagnosis of the ichnospecies *Lavinipes cheminii* and to assign several other sparse tracks and trackways to the same ichnotaxon. *Panguraptor*-like and *Sinosaurus*-like theropods have been identified as most suitable trackmakers for the tridactyl footprints, whereas the sauropodomorph *Gongxianosaurus* has been hypothesized as the most likely producer of *Lavinipes cheminii*. The occurrence of isolated tracks left by large theropods, which autopodium is still unknown in the skeletal fossil record, was also reported. The ichnoassemblage and the possible trackmakers thus suggest a palaeobiogeographic dispersal between Laurasia and the Trento Platform during the Hettangian, providing an accurate constraint to hypothesize their connection through northern and western sectors of Alpine region. Aerial photogrammetry was performed by using Unmanned Aerial Vehicles (i.e., drones) allowed to obtain orthophotos and orthoplanes of the whole tracksite. The map was realized in digital vector format with different level of knowledge with the aim of producing a comprehensive tool. The obtained geothematic map represents a complete documentation that will be useful for future work of enhancement, preservation and valorisation of the tracksite.

## **Sclerobiont Bryozoans from the Maiolica of the Umbria-Marche Domain (Northern Apennines, Italy)**

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*Keywords:* Sclerobiont bryozoans, Maiolica Formation, Umbria-Marche Basin, Northern Apennines, Berriasian.

Sclerobiont bryozoans have been found in the pelagic Maiolica Fm. of the Umbria-Marche Basin (Monte Acuto, Northern Apennines, Italy). The studied specimens, collected as loose material, are three sub-circular colonies of small size with tube-shaped zooecia, radially developing from the centre. Observable characters prevent generic or specific classification and only allow assignation to the Suborder Tubuliporina. Calpionellid assemblages constrain the bryozoan-bearing rock sample to the early Berriasian. This finding represents the first occurrence of isolated bryozoans in the Maiolica Fm., enriching our knowledge about the fauna of this stratigraphic unit in pure basinal settings. The fossil fauna of the unit in fact is commonly composed of radiolarians, calpionellids, dinoflagellate cysts and rare microfossils (ammonites and aptychi), including only very rare benthic organisms (gastropods, brachiopods and bivalves). No sclerobiont organisms in 'normal' pelagic Maiolica facies were known up to date, due to the lack of suitable substrates to be colonised. Based on our material, encrustation of a planktonic or nektonic hard-shelled organism seems the most parsimonious hypothesis supporting this occurrence.



## Modern interoperability concepts applied to the new Geological Structural map of the Serre Massif Upper crust

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*Keywords:* strike-slip kinematics, interoperability, Late-Variscan geodynamics, mylonitic processes.

This work provides the new geological-structural map of the southern Serre Massif (SM), an area extended for ~ 290 km<sup>2</sup>, located within the central sector of the Calabrian-Peloritani-Orogen (CPO). This segment of the CPO is characterized by the presence of a nearly entire Variscan crustal section, presently lying in a tilted position after the final stages of the tectonic uplift, associated with the later surficial stage of the Apennine stage of the Alpine orogeny.

The map fits into this complicated geological-structural context with the aim to clarify the SM geodynamics. The new obtained geological map follows map design rules that aim to the concept of interoperability as one of the most important tasks of the modern cartography, useful to provide geologic maps more consistent in both appearance and database content.

In the last years the interoperability concept and the geological data harmonization have become fundamental, with the statement of several new standards such as GeoSciML data model ([www.geosci.ml.org](http://www.geosci.ml.org)). Therefore, standardization is now essential in the geoscience field because it allows to discuss and share the scientific data easier and faster (Ortolano et al., 2015).

In the present work we used the esriNCGMP Online Geologic Mapping Template, a GIS-based solution that collects together cartography and data structures of the FGDC (Federal Geographic Data Committee), the Esri Geologic Mapping Template geodatabase schema and the NCGMP (National Cooperative Geologic Mapping Program) schema.

The use of this data models was essential to harmonize symbols and terminology that came from different original surveys and it focuses on two important aspects: the information about scientific confidence and locational accuracy of contacts and faults. and the information about data sources.

The “Scientific confidence” expresses a geologist level of certainty regarding the “identity” and “existence” of all features. The “identity” expresses if the observations and data support the nature, origin or geometry of a geologic feature. The “existence” expresses if the observations and data support the continuity or existence of a concealed or unseen geologic feature. Instead, the “Locational accuracy” is based on the relationship between a mapped feature location in the field and its position on the basemap. Therefore, the NCGMP data model clarifies these concepts providing appropriate terminology and symbol styles to adopt in each case.

Ortolano G., Cirrincione R., Pezzino A., Tripodi V. & Zappala L. (2015) - Petro-structural geology of the eastern Aspromonte Massif crystalline basement (southern Italy-Calabria): An example of interoperable geo-data management from thin section-to field scale. *Journal of Maps*, 11(1), 181-200.

# **PhD Day**

*CONVENERS AND CHAIRPERSONS*

## The Italian Geological Society towards an equal and inclusive future

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*Keywords:* Italian Geological Society, PanGEA, diversity, equity, inclusion.

A recent study by Agnini et al. (2020) provided a scenario of the presence of women in the Italian University system in the area of geosciences in the last two decades. Data present a slightly positive trend in the female percentages of both full (from 9.0% to 18.5%) and associate professors (23.6% to 28.9%). Conversely, the same positive scenario is not seen in earlier permanent stages of the academic carrier although the common starting point, the PhD population, shows a substantial gender balance. The under representation of women among permanent researchers (or leaky pipeline) is around 35% but the situation is even more concerning for non-permanent researchers (i.e. RTD-b) which is 32 % in June 2021. Another alarming proxy is the relatively high values of the Glass Ceiling Index (GCI) which estimates the difficulty of women to reach top academic positions that in Italy is up to 3.02 and never approached the value of 1 that indicates no difference between women and men in terms of their chances of being promoted. In conclusion, it is clear that more efforts are needed in order to have a scenario with a substantial gender balance. Promoting work-life balance policies and a firm discouragement of the prevailing patriarchal mentality would eventually help in reconciling family and work so as to give equal opportunities to men and women. On this page, in summer 2021, the SGI created the new Division “PanGEA” dedicated to Diversity, Equity and Inclusion aimed at coordinating and promoting activities and initiatives to overcome differences in gender, sexual orientation, ethnic origin, disability, language and age and support inclusiveness in the Italian Geology. The Division is also conceived as an open environment able to create opportunities for communication, mutual support, professional development and knowledge in a discipline that must evolve to embrace diversity. In particular, the Division is aimed at geoscientists, professionals from the public and private sectors, teachers and lecturers, in order to create a room for dialogue among colleagues, from different generations, and to build up supporting and mentoring actions at different levels. In general, the challenge that the Italian geological world needs to face for the twenty-first century is to promote a new common language that can help everyone to feel closer to Geology and to help geologists to feel fully integrated in the Italian community.

Agnini, C., Pamato, M. G., Salviulo, G., Barchi, K. A., and Nestola, F. (2020) Women in geosciences within the Italian University system in the last 20 years, *Adv. Geosci.*, 53, 155–167, <https://doi.org/10.5194/adgeo-53-155-2020>, 2020.

## The occurrence of carcharodontosaurs in the Apulian Carbonate Platform: new insights from the Early Cretaceous ichnological record of Molfetta (Southern Italy)

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**Keywords:** upper Aptian, lower Albian, theropods, PCA, cluster analysis, palaeobiogeography.

The track-bearing surface of the San Leonardo quarry (Molfetta, Apulia), late Aptian-early Albian in age, is characterised by more than 800 dinosaur footprints. Six bipedal trackways are attributed to theropods whose hip height and body length were estimated up to 1,6 m and 6.5 m, respectively. They are represented by large-sized, weakly mesaxonic and robust tridactyl tracks. Morphological comparison with Late Jurassic and Early Cretaceous theropod tracks from surrounding areas, supported by morphometric analyses, points out a highest affinity with the specimens from North Africa. Nevertheless, a set of unique characters lead to propose the establishment of a new ichnotaxon. The trackmaker's autopodium, reconstructed on the basis of anatomical characters identifiable on the 3D models, allows a reliable osteological match with the known hindlimbs of coeval theropods. Multidisciplinary approaches were combined to identify the most suitable trackmaker: i) phenetic correlation; ii) coincidence correlation; iii) univariate and multivariate analyses, based on more than 600 parameters collected from about 40 species of the main group of theropods. The large and robust hindfoot autopodium hypothesized from the Molfetta tracks rules out the gracile ornithomimosaur and oviraptorosaurs, whereas the comparable length of digits III and IV points to a higher similarity with the hindlimbs of tyrannosauroids and allosauroids. PCA and cluster analyses suggest a close relationship between the reconstructed hindlimb and those of European basal carcharodontosaurs. Although their earliest occurrence was extended back to Late Jurassic of Africa and Europe, the main evolutionary radiation of carcharodontosaurids took place during the Early Cretaceous, when they achieved a cosmopolitan distribution, thus suggesting a biogeographic dispersal between northern and southern landmasses. As a result, the combined data obtained from ichnological and osteological analyses suggest different hypotheses that need to be tested: i) the trackmaker was a Gondwanan carcharodontosaur whose hindlimbs are still unknown from the body-fossil record; ii) the trackmaker was a European basal carcharodontosaur. Whatever the most plausible interpretation, the Molfetta theropod ichnoassemblage strongly confirms the key role of Apulian Carbonate Platform as possible dispersal route between Europe and Gondwana during the Aptian-Albian interval.

## **Further disentangle the role of redox dynamics in black shales: new geochemical observations from the Toarcian Fish Level (Sogno Core - Lombardy Basin, northern Italy).**

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*Keywords:* T-OAE, black shales, geochemistry.

The early Toarcian Oceanic Anoxic Event (T-OAE) was associated with major climatic changes involving profound effects on the global carbon cycle that occurred ~183 Myr ago. During the early Toarcian, sedimentation in the Lombardy Basin (Southern Alps, northern Italy) was characterized by the deposition of the Fish Level (Livello a Pesci), a dark grey to black marly claystone characterized by low CaCO<sub>3</sub> content and relatively high TOC content.

The literature describes a drastic climatic and palaeoceanographic revolution during the T-OAE; however, quantification of the rates, duration, lag-times and local expressions of the environmental and biological response are not yet fully understood.

Here we present a detailed organic geochemical characterisation of the Fish Level recovered through coring at Colle di Sogno (Sogno Core). The Sogno Core can be considered a reference section for the pelagic lower Toarcian interval of the Western Tethys. It recovered a 26.83 meter-thick pelagic succession comprising marly limestones, marlstone, marly claystone, and a relatively expanded black shale interval of 4.98 m (Fish Level) with lower and upper boundaries without evidence of hiatuses. Nannofossil biostratigraphy and carbon isotopic chemostratigraphy allowed a detailed characterization of the uppermost Pliensbachian – lower Toarcian interval. The Fish Level is divided into three distinct lithostratigraphic intervals that document a progressive upward increase in total organic carbon (TOC) reaching values up to ~2.5% in the uppermost part. High-resolution sulphur, iron, organic carbon, and specific (aliphatic) biomarker data, along with Rock-Eval parameters of the upper Pliensbachian-lower Toarcian interval allowed the reconstruction of variations in redox state, organic matter type, carbon burial trends and the potential impact of thermal maturity and sulphur bacterial degradation affecting the original TOC. Notably, we explore how variations in oxic, sub-oxic-anoxic and strictly anoxic-euxinic environmental conditions are linked to organic matter quality and preservation within the black shales interval. These new geochemical observations from the Fish Level contribute to shed new light on outstanding questions concerning the extent of ocean anoxia/dysoxia in the Tethyan area.

## **Stratigraphic, structural and metamorphic characterization of tectonic units in the Western Alps**

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*Keywords:* Western Alps, tectono-metamorphic evolution, phase equilibria modeling.

My PhD project focuses on the Alpine units exposed between the upper Susa and Chisone valleys in the Western Alps with the main scopes 1) to constrain the significance of their lithostratigraphic successions and relationships within the Jurassic rifting-related paleogeography and 2) to better define their tectono-metamorphic Alpine evolution and relationships.

The investigated Alpine sector includes distal continental margin successions (e.g. in Monte Banchetta and Monte Furgon areas) and slivers of oceanic basement (e.g. in M. Albergian-Gran Mioul, Colle del Beth, Col Clapis, M. Cruzore, and Lago Nero areas) with their meta-sedimentary covers.

Accurate geological mapping was carried out in several key areas (e.g. Troncea and Chisonetto valleys, upper Chisone and upper Massello valleys, lower Thuras and upper Argentera valleys and Cesana Torinese area) and they were of primary importance to identify the relative paleogeographic position of rock volumes involved in the Alpine orogenic processes. In particular, the ongoing research revealed a tectonic unit (Monte Banchetta – Punta Rognosa tectonic unit) consisting of continental crust and exhumed mantle both covered by the same post-rift sediments.

Petrographic analyses, mineral chemistry and isochemical phase diagrams modeling (i.e. pseudosection modeling) are being used to define the Alpine P-T path of the studied units. The obtained results show juxtaposition of units with different metamorphic peaks, with large difference in peak P-T conditions, in the epidote field for some units and in the lawsonite field for other units. On the other hand, these units seem to have shared a common evolution since the first stages of their exhumation history.

In particular, preliminary results suggest to extend westward, compared to current knowledge, the eclogite-facies metamorphism in this sector of the Alpine belt, implying then an overall complex interpretation of the subduction and exhumation processes at a larger scale.

## **Automatic X-ray image analysis of rock samples: a machine learning approach to explore geoscience data**

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*Keywords:* Machine learning, X-ray maps, Python.

In recent years, computers performance has improved significantly. This allows the scientific community to have access to increasingly sophisticated IT tools for data analysis, capable of processing an ever-increasing amount of information. The term “machine learning” encompasses a wide variety of artificial intelligence algorithms. While some of them (i.e., supervised algorithms) are able to learn the proper way of recognizing and classifying certain objects through the “experience” provided by the operator, others (i.e., unsupervised algorithms) are instead capable of identifying hidden patterns within data without any suggestion from the operator. This PhD project aims to apply these algorithms to the study of geoscience data, with a particular reference to the mineralogical field. Instruments such as SEM-EDS or EPMA-WDS allow indeed to extract semi-quantitative chemical maps from rock thin sections. The chemical data thus obtained can be examined by the operators to infer the occurring mineral phases. This is a rather time-consuming procedure and suffers from the subjectivity of the operators themselves. By appropriately training a supervised machine learning algorithm, it is possible to fully automate this process. At the current stage of the project, we took advantage of python programming language to train several learning models capable of extracting 2D mineralogical maps from X-ray maps in few seconds and achieving a classification accuracy that ranges between 90% and 95%. At the same time, we proceeded with the designing of a computer software, whose aim is to display the input maps (i.e., X-ray maps) and interactively apply the learning models to obtain the mineralogical output maps, making use of a simple and intuitive graphical user interface. In the near future we expect to implement unsupervised machine learning algorithms to extract further information from recognized mineralogical classes, such as the presence of intra-mineralogical variations (e.g., mineral zoning). Furthermore, we plan to expand the methods of data analysis and collection, by including micro-tomography analysis techniques. Micro-CT data, indeed, if made properly interact with the X-ray maps, could allow the extraction of 3D mineralogical maps. In our opinion this PhD project could have significant repercussions both on a purely academic level as well as on the industrial mining sector.



## **High-resolution calcareous nannofossil biostratigraphy of Neogene successions: comparison between Mediterranean and ocean realms**

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*Keywords:* Mediterranean, calcareous nannofossils, Neogene.

Calcareous nannofossils are widely used for correlation of marine sediments at a global scale.

In recent time a good set of biohorizons have been established, on the basis of quantitative analyses, for the correlation of Neogene marine sediments characterizing the Mediterranean Neogene region, chronologically constrained through the integration of “time diagnostic” tools, such as magnetostratigraphy and astrochronological calibration.

So far, integrated stratigraphic data from several Mediterranean sections are available, such as La Vedova, La Contessa and Trave in Central Italy, Contrada Pesciareello and M. Gibliscemi in Sicily, St. Thomas and St. Peter's Pool and Ras-il-Pellegrin in Malta, S. Nicola in the Tremiti Islands, Faneromeni and Metochia in Greece, Oued Akrech in Morocco, DSDP Site 372 in Western Mediterranean, for the Miocene time interval, and ODP Legs 160 and 161 for the Plio-Pleistocene one.

These data contribute to establish refined biostratigraphic schemes for the Neogene of the Mediterranean region, which significantly improve the resolution of the standard schemes established in the 70s and 80s exclusively in oceanic sediments (e.g. Martini, 1971; Okada and Bukry, 1980), and which have shown little applicability in Mediterranean deposits, due to paleogeographic reasons.

Nevertheless, some time intervals (such as Aquitanian/Burdigalian; Zanclean/Piacenzian) still remain characterized by low biostratigraphic resolution. The present research intends to identify the time intervals affected by low biostratigraphic resolution, as regards the calcareous nannofossils, and to find marine sequences falling within those intervals, in order to carry out quantitative analyses to be integrated with other data, such as paleomagnetism or astrochronological tuning.

The aim is to find out a higher number of reliable nannofossil biohorizons, chronologically constrained, useful for stratigraphic correlation, both in the Mediterranean and oceanic realm.

About this, another open question remains the comparison of the events recognized in the Mediterranean area and their exportability in oceanic areas, especially in the still little-known Southern Ocean region. For this purpose, the succession of Leg ODP 1123 will be studied, located off-shore of New Zealand, which represents one of the best representative marine successions of the last 20 million years. The succession contains excellent and well-preserved associations with nannofossils and is accompanied by extraordinarily good data on paleomagnetism.

The aim is to reconstruct a biostratigraphic scheme based on nannofossils for the Southern Ocean area and to make a comparison with those established in the Mediterranean region, in order to identify bioevents that can be used for correlations on a global scale, considering the enormous geographical distance between the two areas chosen for comparison.

## **The impact of climate change on groundwater temperature of the Piedmont Po plain (NW Italy): preliminary results**

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*Keywords:* groundwater temperature, climate change, Po plain.

It's now recognized that a global climate change is taking place, leading to an increase in temperatures and a variation in precipitation regime, also affecting groundwater (GW).

In this study we want to evaluate how climate change affects GW temperature in the Piedmont Po plain (NW Italy).

The Piedmont Po plain covers the 27% of the whole region and it's the most important GW reservoir of the Piedmont region (De Luca et al., 2020). It consists, from top to bottom, by Alluvial deposit complex (lower Pleistocene-Holocene), that hosts a shallow unconfined aquifer, the "Villafranchiano" transitional complex (late Pliocene-early Pleistocene), that hosts a multilayered aquifer, and a Marine complex (Pliocene) hosting a confined aquifer.

For this research, 41 wells in the shallow aquifer and 20 weather stations were selected throughout the Piedmont Po plain area, and GW and air temperature parameters were analysed for the period 2010-2019.

The GW temperature data were firstly studied with basic statistical analysis (mean, maxima, minima) and then with the Mann-Kendall and Theil-Sen methods to evaluate the trend of the monthly mean GW temperatures. GW temperatures show a general increase in all the plain, up to a maximum of 2.18 °C/10 years. The same analyses were carried out for the air temperature data and it was observed that the increases vary between 1.52 and 2.11 °C/10 years.

Then to compare water and air temperature, the Voronoi polygons method was used on QGis by centring the polygons on the weather stations. From this comparison, it was possible to highlight that in most cases (37 on 41, thus 90% of the analysed couples of temperature data) there is a greater increase in the monthly mean air temperatures than in the monthly mean GW temperatures.

The same behaviour was observed for the monthly minima and maxima GW and air temperature.

These results testify a greater resilience of GW temperature to climate variability. Future insights will be a detailed analysis of the factors influencing the more or less evident increase in GW temperatures in relation to air temperatures (e.g. depth of the water table, position of the monitoring well, position of the probe inside the well...).

## Sicily as a pilot region for micro-zonation of the low-enthalpy geothermal potential

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**Keywords:** Geothermal energy, low-enthalpy, Sicily.

The constant increase of energy demand requires a redefinition of the energy use according to unconventional forms of exploitation. In such a context, low-temperature geothermal energy investigations play a key role. The main objective of the present project is to evaluate the low-enthalpy geothermal potential in Sicily through the definition of 3D geological and thermal models of the regional domain and local contexts. These models will be propaedeutic to 1) investigate the lithospheric setting; 2) the numerical simulation of subsurface heat transfer; 3) quantifying the subsoil thermal regime; 4) defining the actual possibility of exploitation in pilot sites. The research, which is involved within the framework of the Innovative Ph.D. programs with industrial characterization (PON Research and Innovation 2014-2020 Action I.1), envisages collaborations with the German Research Centre for Geosciences (GFZ), Potsdam, Germany, and Eartherm s.r.l., a spin-off enterprise of the University of Catania. The research starts from the study of a multi-scale detailed geological framework and a wide geophysical background (national exploration surveys and new gravimetric and magnetic datasets recently acquired). A 3D lithospheric-scale model of a 300 × 400 km extended area in the central Mediterranean domain (Lat38°, Lat35°) and depth of 80 km, which is consistent with the available geological and geophysical data and the observed gravity field, will be obtained. The same approach will be then exported for a pilot zone (about 20 × 20 km in extension) that represents an emerged carbonates domain, the so-called Hyblean foreland (South-East portion of Sicily). The 3D geological models have been developed through the collaboration of the basin modeling section of GFZ of Potsdam and provide the boundary conditions for the subsequent geothermal evaluation. 3D geological models (based on gravimetry and seismic tomography conversion) will provide the basis for the lithospheric setting below the Sicily domain as well the thermal constraints for local site and models at higher resolution. In light of the gravity and thermal constraints, thermal numerical simulators for the modeling of geothermal properties (through the use of algorithms developed at GFZ) will be implemented. This will enable us to solve variations in heat

transfer, reconstructing the temperature distribution at depth and to investigate the radiogenic heat production of the shallow crust, which is an essential information to improve our knowledge of the geothermal potential at shallow/intermediate depths. As a result, low-enthalpy geothermal mapping of shallow resources within suitable areas will be produced. The collaboration with Eartherm s.r.l will also allow the analysis and optimization of exploitation methodologies.

## **Evolution of the West Antarctic Ice Sheet from the inner continental shelf of the Glomar Challenger Basin to the Ross Sea slope (Eastern Ross Sea, Antarctica) during the late Quaternary**

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*Keywords:* Antarctica, Ross Sea, sedimentology.

Studying the sedimentary sequence of the Ross Sea is fundamental to reconstruct the evolution of the West Antarctic Ice Sheet (WAIS). The WAIS advanced and retreated many times during glacial and interglacial periods. The presence of glacial and sub-glacial features on the continental shelf indicates that the WAIS advanced across the shelf up to the shelf break in many sectors of the Western and Eastern Ross Sea (WRS and ERS) during the Last Glacial Maximum (LGM). However, the Ross Sea history is still under investigation and especially the post-LGM retreat is still debated. Sediments deposited during the late Quaternary on the continental shelf and along the continental slope could help to reconstruct the ice sheet evolution during such a crucial time frame.

This project aims to study cores and box cores collected in the ERS, along the Glomar Challenger Basin, from the Ice shelf to the Ross slope east of the Hillary Canyon, in order to reconstruct the late Quaternary history of this sector of the WRS. This area is a key sector because the Hillary Canyon carves the ERS continental slope and is connected to the Glomar Challenger and Pennell Troughs on the shelf, south-east to the Iselin Bank, which are strongly related to sedimentary drainage of the ice sheet and inflow/outflow of polar water masses. Multidisciplinary analysis, such as grain size, organic matter, biogenic silica, water content, magnetic susceptibility, chemical composition (XRF core scanner), clay analysis will be conducted in order to reconstruct the sedimentary dynamics. Foraminifera, if presented and well preserved, will be identified at species level, allowing to reconstruct paleoceanography, paleobathymetry and paleotemperature. Isotopic analysis ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$  and Mg/Ca ratio) will be performed on calcareous tests and dates ( $^{14}\text{C}$ ) will be performed on both calcareous tests and organic matter (AIO). Some cores and box cores were previously partly studied but adding more analysis, applying new techniques and increasing the stratigraphic resolution will be very useful to reconstruct the ice sheet dynamics.

This PhD project is supported by two ongoing projects: the STREAM Project (Late Quaternary evolution of the ocean-ice sheet interactions: the record from the Ross Sea continental margin, Antarctica; period 2019-2021) funded by the Italian Ministry of Foreign Affairs and International Cooperation and the National Research Foundation of Korea and the ANTIPODE Project (Onset of Antarctic ice sheet vulnerability to ocean conditions; period 2020-2022) funded by MIUR.

## Walk to learn, learn to walk: an educational practice to reconnect geology with sustainability

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*Keywords:* environmental education, sustainability, transdisciplinarity.

Despite the fact that, at the dawn of XXIst century, many scholars were predicting a central role of earth sciences (ES) in the education for future citizens and in the scientific inquiries, the geology community has almost missed the opportunity to have a real impact in societal problems and to be considered at the centre of a new kind of education, where the geoscientists skills could be helpful to prepare for the future. In particular, the sustainability wave seemed to leave ES behind, as it's easy to understand considering the deep lack of geology classes in high ranked degrees and the decreasing number of students that applied for ES in the last years. Surely there's a problem with geosciences education in national curricula: nonetheless, it's time to change our approach as educators and give more importance to the complex and systemic abilities that we can develop. ES education needs a shift to move towards a sustainable, transdisciplinary and more experiential approach.

Walking can be a good starting point. If "educate", referring to the original Latin *educere*, means to experience "outside" in the world, it means also to be able to discover a territory with a sensorial approach. Geoscientists know, more than others, the importance of reading a territory as a complex system, where geological aspects are connected with others. Furthermore, the experience of crossing a territory in a group allows to go beyond the classic one-way transmission of notions and leads to a mutual exchange of shared knowledge on the same experiential level.

During may 2021 we proposed to students a two-day workshop called *Walking hills*. The workshop consisted in two different treks in Turin: the first one was a round-trip around Superga; the second in Western Monferrato, headed to the romanesque Abbazia di Vezzolano. During these two days we move on a territory with a high geological richness, where students can observe different typologies of outcrops. Nevertheless, we explore the historical and artistic landscape of the area. This workshop was an experience of a transdisciplinary educational project based on a systemic approach, to promote education as the discovery of interactions, a place where teachers and learners tried to break conventional boundaries between scientific and humanistic approach, nature and culture, even body and mind. A quantitative and qualitative analysis of data collected by questionnaires and interviews with students shows that this approach helps to reconnect geosciences with education for sustainability.

## **Gravitational, Erosional Sedimentary and volcanic processes on the submarine environment of Flores and Corvo islands (Azores archipelago)**

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*Keywords:* Azores Archipelago, volcanic oceanic islands, submarine geomorphology.

This project aims to improve our understanding of the geological evolution of volcanic islands by means of an integrated onshore/offshore approach, using as case study the islands of Flores and Corvo in the Azores. To achieve this aim, there will be interpreted data with an unprecedented coverage and resolution, yet to be explored, including subaerial (geomorphology and geology) and submarine datasets (multibeam bathymetry, high-resolution reflection seismic profiles and sediment samples). This study focuses on the most important processes that control submarine morphology (wave erosion, volcanic progradation, masswasting, sedimentation and canyon incision), so the project will contribute to the comprehension of the geological evolution of volcanic islands, through a truly integrated Earth system science perspective, by investigating the relationships between volcanic, tectonic and erosive-depositional processes. Finally, the societal importance of this study is two-fold given that the coastal zones of volcanic islands, where most of the population is concentrated, are the arena of: (i) hazards, such as marine erosion on a rising sea level, tsunamis associated to subaerial/submarine landslides; and (ii) exploitation of sediments and biological communities (both important resources for the insular economies, respectively marine aggregate's extraction and fishing). Furthermore, it can provide the tools for adequate policy decision-making to protect and explore these natural systems, meeting the goals 13 and 14 of the 2030 Agenda of the United Nations Sustainable Development.

## **Evidence of syndepositional tectonics during the Early Permian in the Orobian Basin (central Southern Alps, N Italy)**

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*Keywords:* Permian tectonics, synsedimentary deformation, low-angle normal fault system.

Proofs of synsedimentary tectonics during the Early Permian in the central Southern Alps (cSA, N Italy) are recorded in the volcanic and terrigenous successions of the Laghi Gemelli Group, which are characterized by the occurrence of abrupt facies variations often associated with coarse-grained deposits. These features are generally attributed to syn-sedimentary tectonic activity demonstrated by the local occurrence of sediments deformation such as liquefaction or slumping due to seismic shaking. Detailed fieldwork allowed us to recognize dewatering structures and sedimentary dikes, ball and pillars and small slumps, occurring along hundreds of mesoscopic faults showing meter-scale displacement in correspondence of high-angle conjugate systems as well as domino-style faults, often accompanied by growth structures. These structures are mainly concentrated in the fine-grained sediments of the Pizzo del Diavolo Formation, which were deposited on top of the volcanoclastic succession of the Ca' Bianca Volcanite and crossed by seismogenic synsedimentary faults. The Permian synsedimentary structures of cSA are mostly associated with high-angle Andersonian normal faults which are combined with low-angle normal faults (LANFs) that developed along the interface between the Permian sedimentary cover and the Variscan basement. This LANFs system is relevant for the Permian hydrothermal circulation, resulting in widespread tourmalinites deposition along fault zones, and locally in U mineralization. According to our structural analysis the Permian tectonic setting is characterized by pure extension, dominated by ENE-WSW striking normal faults inverted during the Alpine shortening as high-angle reverse faults.



## Surface waters, suspended solids, and sediments from the Nievole River Valley sub-basin (Tuscany, Central Italy): a preliminary environmental evaluation

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Keywords: water geochemistry, heavy metals, isotopes, Nievole River Valley.

The Padule di Fucecchio (Tuscany, Central Italy) is located in the lower reaches of the Nievole River Valley. It represents a protected swampy zone that plays an important role in the migratory routes of several bird species. The study area is positioned within the complex riverine network composed by the Nievole, Pescia di Collodi and Pescia di Pescia rivers, including many artificial channels that crosscut the western part of the basin, and collects effluents from many small cities and industrial districts. The Padule di Fucecchio waters are fed by the Usciana River, which is an artificial channel built in 1934 and represents the only emissary of the swampy area that, after 25 km, flows into the right bank of the Arno River. All the sub-basins are complex ecosystems characterized by many relevant anthropic activities and small-medium enterprises, such as paper mill industries, flora-nursery farms and one of the most productive Italian tanning districts, making this zone one of the most polluted district of the Arno River Basin.

The main aim of the PhD project is to define the anthropogenic and natural contributions that affect the surface waters, suspended solids load, and sediments of the Nievole River Valley, Padule di Fucecchio and Usciana River using major, minor, and trace elements, Pb-Nd-Sr isotope data.

We present some preliminary results on the evaluation of the water and suspended solids load quality in the Nievole River Valley. Water samples, suspended solids, and sediments samples were collected along the main course and tributaries distributed in an area of about 320 km<sup>2</sup>. Temperature, pH and electrical conductivity were measured in the field with a multi-probe portable probe. Alkalinity was determined by volumetric titration while N-species were measured by molecular spectrophotometry. Major and trace elements were determined by Ion Chromatography (IC) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), respectively, while radiogenic isotopic ratios in the water and suspended particulate samples were analyzed by Thermal Ionization Mass Spectrometry (TIMS). Water chemistry showed a relatively wide variability since Ca<sup>2+</sup>(Mg<sup>2+</sup>)-HCO<sub>3</sub><sup>-</sup> to Na<sup>+</sup>-Cl(SO<sub>4</sub><sup>2-</sup>) geochemical facies were recognized. The N-bearing species were characterized by concentrations up to 36 (NO<sub>3</sub><sup>-</sup>), 2.4 (NO<sub>2</sub><sup>-</sup>) and 11.5 (NH<sub>4</sub><sup>+</sup>) mg/L, while those of Mn, Fe, and Cs were up to 595, 432, and 36.7 µg/L, respectively. As far as the metal content in the suspended solid load, Cr and Zn revealed the highest concentrations (up to 429 and 409 mg/kg, respectively). Nickel, V, Pb, Cs, and As showed values up to 120, 149, 83, 46, and 25 mg/kg, respectively. According to Legislative decree 152/2006, the heavy metal concentrations for the suspended solids data approach or are higher than those for the Italian soils intended for green public areas suggesting that a strong anthropogenic pressure is acting on the Nievole River Valley.

## First steps toward the definition of the deep structure and dynamic of the circum-Mediterranean orogens

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Keywords: 1D Minimum velocity model, AlpArray project, geodynamic, central-Mediterranean.

The Alp-Array project is an European initiative to advance our understanding on the deep structure and dynamics of the circum-Mediterranean orogens elucidating the interaction between the Alps and the surrounding Apennines, Dinarides and Carpathians orogens. Still today, there are many debates and open questions on the deep geometry and links between those belts. One of the controversies is the slab origin and polarity beneath eastern Alps, between the opposite models of Adria or Europe subduction.

Some broad tomographic images of the circum-Mediterranean orogens are already present in the literature but those models have an intrinsic low resolution. So, the goal of our study is to obtain a high-resolution tomographic model to better solve the dynamic and the deep geometry of these belts. The main idea is to compute models of  $V_p$  and  $V_p/V_s$  perturbations to directly temperature and compositional variations in the mantle. In this way, it will be possible to have more constraints for geodynamic processes in the central Mediterranean, as for example the subduction processes. To study these last through a multidisciplinary approach, we will build also analogical models at the LET (Laboratory of experimental Tectonics) of Roma Tre University.

In this study, we present a preliminary analysis of a huge data set collected from recordings at 628 Alp-Array seismic stations, which is the biggest broad band seismic network ever operating in Europe. A total of 61 institutions and 11 European countries have made available their permanent seismic stations and have installed new temporary stations to obtain a dense seismic array. These stations recorded in continuous for two years (2016-2018). We selected only seismic events with a value of magnitude ( $M_w$ )  $\geq 3.5$ , recorded by all the seismic stations operating in the area. This dataset has been extended with some relevant ( $M > 4$ ) seismic events recorded between 2014-2021 from the Italian National Seismic Network (RSN).

Here, we present the computed one-dimensional Minimum velocity models for sub-regions and for the entire Italy, obtained inverting selected events with the VELEST procedure, and some early tomographic images of the Central Mediterranean area. The entire Italy was divided in four sub-regions: Alps, Northern Apennines, Southern Apennines and South Italy, accounting the data distribution and the differences in the geology. These velocity models were used to relocate the Italian seismicity of the past 5 years (2015-2020) and as reference model to compute 3D tomographic images.

## Triggering dynamics of explosive eruptions at Stromboli volcano: nature and spatial-temporal constraints of replenishment processes with implications for the Early Warning system setup

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**Keywords:** paroxysmal activity, magma degassing, melt embayments.

The eruptive behaviour of Stromboli makes difficult the understanding of mechanisms driving the temporal transition from the ordinary Strombolian activity to violent explosions (e.g., major explosions and paroxysms). The eruptive phenomena arising from these mechanisms often occur without clear precursors signals of warning. This research project has the following objectives: 1) definition of the nature and of the spatial and temporal relationships of processes that move the state of ordinary activity of the volcano towards more energetic manifestations (major explosions and paroxysms); 2) reconstruction of the current working model of the volcano; 3) identification of “sentinel parameters” based on a multi-parametric investigation approach based on the integration of petrological, geochemical and geophysical data. Methods adopted for the sample investigation are aimed at: 1) sampling the periodic (weekly-monthly) pyroclastic material of the ordinary Strombolian activity (summer-autumn 2021), with acquisition of the petrological dataset on products deriving from potential major explosions and paroxysmal activity within the period; 2) analysing the textural and micro-compositional characteristics of mineral phases (olivine, plagioclase, clinopyroxene) for the determination of major (EMPA, SEM-EDS/WDS) and trace elements (LAICP-MS) in order to reconstruct the storage and transfer dynamics of magmas throughout the plumbing system; 3) analysing the melt inclusions and embayments in olivine to get concentrations of major elements (EMPA, SEM-EDS/WDS), trace elements and H<sub>2</sub>O, CO<sub>2</sub>, S, Cl, F (nanoSIMS) in order to reconstruct the degassing dynamics during the final transfer of magmas upward to the surface; 4) defining the kinetic model related to degassing based on the ultra-fast diffusion of trace elements and volatiles in crystals and melt embayments. The study of melt inclusions will provide fundamental information on the physical-chemical nature of fluids in the plumbing system. Diffusion models will be applied to obtain the timescales of magma ascent especially through the analysis of the chemical zoning of volatile species in both melt inclusions and embayments. Since magma ascent to the surface is expected to be quite rapid, only fast-diffusion volatile components can fix the temporal development of processes. The obtained dataset, combined with data coming from gas monitoring and ground deformations, will contribute to the development of the final working model. The available data will be also used to refine the *Early Warning System* through the identification of some new precursory signals.

## **An integrated approach to assess the physicochemical properties of carbonate rocks for CO<sub>2</sub> storage: a case study from Central Apennine (Italy)**

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*Keywords:* carbonate reservoir, petrophysical characteristics, CO<sub>2</sub> storage.

From several years, carbon dioxide capture and storage (CCS) is progressively becoming more relevant in addressing the environmental needs derived by global warming and climate change. In particular, the CO<sub>2</sub> stored in geological formations is considered as a valid method for considerably reducing the release in the atmosphere of waste CO<sub>2</sub>. Until now, underground storage of CO<sub>2</sub> has been employed in different parts of the world in particular combined with the enhanced oil recovery practice. Only recent studies investigated the impact of CO<sub>2</sub> injected in different reservoir rocks for assessing their potentiality to act as repositories and natural catalyst for the CO<sub>2</sub> conversion into new useful fuels. However, the geological formations are strongly influenced by the presence of CO<sub>2</sub> since it leads to a disequilibrium of both fluid chemistry and pore pressure, triggering to a series of geochemical reactions which result in a new minerals assemblage and arrangement of the petrophysical properties. In particular, when carbonate minerals are involved, these variations are enhanced due to their high reactivity with water-saturated CO<sub>2</sub>, with respect to a siliciclastic component. The case study here presented is referred to the dolomitized units cropping out in the Castel Manfrino area (Central Apennine, Italy), which offer an opportunity for studying the reservoir quality as a function of different dolomite textures, resulted from several dolomitization events. The first data has been obtained coupling petrographic analysis and techniques as X-ray Powder Diffraction and synchrotron X-ray phase-contrast microtomography. The acquire data allowed to distinguish between high and low-quality reservoirs focusing on different parameters such as mineral textures, pore size distribution and connectivity of the inter-crystalline porosity. Furthermore, a strong control on the type of dolomite texture and size of crystals by the original facies of the precursor limestone has been highlighted. At the same time such characteristics can be affected by different processes of dissolution and precipitation of new minerals, modifying the physicochemical properties of the different phases involved. For this reason, Raman and FTIR spectroscopy analyses have been performed, providing preliminary results concerning the main mineralogic phase and the elements distribution through the carbonate rocks in order to predict the CO<sub>2</sub>-water-rock interaction and verify the availability of catalyst elements. This last approach has been extended also to calcareous rocks not affected by dolomitization (e.g. Calcarea Massiccio Fm, Umbria-Marche Apennine).

## **Review and comparative analysis of available fault database for the territory of N. Macedonia**

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*Keywords:* faults, tectonics, seismicity, seismic hazard, N. Macedonia.

N. Macedonia as a country has a rather long history in the domain of seismic hazard assessments, implementing and testing different seismic hazard models and assessment methodologies, in order to provide the most reliable seismic hazard assessment. Predominantly, previously used seismic hazard models at the national level consisted of aerial type or gridded seismicity sources, mostly due to the lack of consistent and reliable seismogenic active fault parameters. The purpose of this study is to summarize and comparatively analyze all up to date available national (Basic Geological Map 1:100,000), and regional and European (EDSF13) fault parameterization data, to extract the gaps and inconsistencies, and to propose alternative state-of-the-art methodologies to be used for seismogenic active fault parameterization. Being aware of the lack of new and modern geological, tectonic and seismological data, the possibility of proposing alternative methods for fault characterization and classification based on geodetic strain rates and satellite data is being considered. The recommendations from such a research will ultimately contribute to increasing the probability of determining the seismic hazard, as well as will have a direct practical application in the seismic design regulations, given that N. Macedonia recently adopted the European design regulations (Eurocodes).

## **Structural-thermal constraints in the hinterland-foreland transition zone: new insights from the Nappe Zone of the Sardinian Variscan belt**

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*Keywords:* Nappe Zone, Variscan Belt, structural geology.

In collisional belts, the transition from hinterland to foreland is considered a key area to understand the tectono-metamorphic and exhumation history of the middle crust. This area represents the transition from tectonic units occurring in the metamorphic core of the belt (hinterland) to the ones deformed at higher structural levels, progressively incorporated in the orogenic wedge. This sector is characterized by the development of folds, tectonic contacts and large-scale nappe stacks with different metamorphism and diachronous evolution. Nappe boundaries are marked by regional-scale shear zones that accommodate large displacements allowing crustal slices to reach different metamorphic conditions. Several uncertainties in unravelling the burial and exhumation history of these rocks arise from the complex overprinting pattern of post-collisional deformation that modified the original attitude of the structural elements. The Variscan Belt in Sardinia is a good site to investigate the tectonic mechanisms acting during the evolution of collisional-type orogenesis since the area has not been strongly reworked by the later Alpine orogenic cycle. The Sardinian nappes have been subdivided into External (central to southern Sardinia) and Internal (central to northern Sardinia) Nappe Zones. These tectonic units were emplaced during the Early Carboniferous with a top-to-the S-SW sense of thrusting and, in the study area, they are mainly made of a polydeformed low-grade metasedimentary sequence with few metavolcanic rocks and marbles. The Internal Nappe Zone, in the investigated area is represented by the structurally upper Barbagia Unit (BU; often indicated as the Low-Grade Metamorphic Complex) overthrust above the Meana Sardo Unit (MSU), belonging to the External Nappe Zone. The boundary between BU and MSU is marked by the Barbagia Thrust (BT), a regional-scale ductile to brittle shear zone. We characterized in detail both meso- and microstructural features of the BU, MSU and the BT high-strain zone. Four ductile deformation phases have been detected. Due to the ubiquitous occurrence of organic material in the study area, the peak temperature has been quantified by the Raman Spectroscopy of Carbonaceous Material (RSCM). The study of temperature through RSCM is fundamental to detect metamorphic conditions both in the high-strain zone linked to the BT and in BU/MSU, as well as, to highlight some thermal anomalies linked to specific geological settings. Integrating these methodologies, we characterize the structural architecture, kinematics, the deformation temperature and its areal distribution, of this portion of the European Variscan Belt.

**Relationships between shear zones, mechanisms of emplacement and structural evolution  
from supra- to sub-solidus of late-Variscan granitoids  
from the Serre Batholith (southern Italy)**

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*Keywords:* microstructures, AMS (anisotropy of magnetic susceptibility), EBSD (electron backscattered diffraction)

Serre Batholith granitoids in central Calabria constitute the intermediate portion of a continuous section of exhumed Late Hercynian continental crust. They emplaced at depths between 6 and 23 km through an overaccretion mechanism which saw first the emplacement of quartz-diorites and deeper crust tonalites (c. 297 Ma), followed by granodiorites and strongly peraluminous porphyritic granites of intermediate crust (c. 295 Ma) and finally, at c.292 Ma, of granodiorites and slightly peraluminous equigranular granites. The emplacement of these bodies took place along shear zones whose kinematics remains debated today. The granite rocks have variously recorded the oriented stresses that affected the batholith during and after the emplacement of the magmatic bodies. Evidence of an increase in the X/Z ratio of the strain ellipsoid as the depth of emplacement of the granitoids increases was obtained through microstructural investigations, distinguishing older strongly foliated granitoids belonging to deeper crustal domains from weakly foliated up to more recent non-foliated granitoids and emplaced in more superficial crustal domains. However, the analysis of the oriented fabric with traditional survey techniques (e.g., optical microscope) is often ineffective or completely impractical on apparently isotropic granite rocks. For this reason, the present study proposes the integration of traditional techniques with alternative investigation techniques such as AMS (anisotropy of magnetic susceptibility) and EBSD (diffraction by electronic backscatter) to characterize the fabric in batholith granitoids, determining their preferential crystallographic orientations despite they are apparently invisible. In fact, techniques of this type have been applied to a limited extent on these rocks, some of which also lack basic microstructural analyses. The proposed approach will allow to obtain the information necessary for a better understanding of the relationships between regional deformation, emplacement of granite bodies and their structural evolution in conditions from submagmatic to subsolidus.



## Palaeoenvironmental and palaeogeographic evolution of Southwestern and Central Iran during Palaeozoic

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*Keywords:* Palaeozoic, sedimentary geology, Iran.

The Iranian territory is a strategic area for the study of the Phanerozoic, derived from a series of geodynamic events and the convergence of three main structural units. Thick sedimentary successions, ranging from Cambrian to the recent, include also some of the main hydrocarbon systems of Middle East. In this view, geological investigations in Iran were focused mainly on the more accessible Mesozoic and Cenozoic units, while Palaeozoic successions lack a detailed sedimentological and stratigraphic assessment. This project aims to improve the palaeogeographic knowledge of the Iranian Palaeozoic by integrating the literature data with new analysis on sedimentology, sequence stratigraphy and biostratigraphy. In particular, five Cambrian Ordovician and five Permian key sections were investigated in terms of facies, microfacies, organic facies and palynological assemblages. During the lower Palaeozoic, both the Zagros and Central Iran basins were located in the north-eastern margin of Gondwana, an area characterized by tectonic quiescence for most of Cambrian and Ordovician time interval. The eustatic sea level rise led to a progressive flooding of the region, and the late early Cambrian fluvial to coastal depositional settings were replaced by an extended epeiric basin. During middle and late Cambrian, a carbonate ramp developed, evolving into a storm-dominated siliciclastic shelf from late Cambrian to Middle/Late Ordovician, after major maximum flooding events and climatic changes. The latest Ordovician glaciogenic regression, together with the next younger Hercynian orogenesis, caused prolonged exposure and important erosional processes which are the reasons that Silurian to Carboniferous deposits are poorly developed in Iran. In the late Carboniferous/early Permian, the extensional tectonics related to the Neo-Tethys opening created new accommodation space and the recovery of sedimentation over major regional unconformities. Central Iran drifted away from the Zagros (south-eastern Pangea margin), migrating northward as part of Cimmerian terranes. In both Neo-Tethys sides, widespread carbonate platforms evolved throughout the middle and uppermost Permian. The carbonate system recorded a crisis evidenced by an abrupt increase in shale deposits which marks the P/T transition in Central Iran. In the earliest Triassic, the carbonate production fully recovered with the developing of thrombolyticstromatolitic boundstone. The integrated sedimentological and stratigraphic approach used in this study was fundamental to define the development of small to large scale depositional sequences and their association with respect of autocyclicity, eustatism, tectonics and climate changes. Furthermore, this study found out the similarities and differences in the depositional evolution of Iran and the adjoining areas (e.g.: Arabian Peninsula, Turkey, Iraq, Syria) providing new constraints on the palaeogeographic evolution of the Middle East during Paleozoic.

## **High mountains, human activities, and climate change: multitemporal field monitoring along routes and around refuges of the Monte Rosa massif.**

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*Keywords:* glacial geomorphology, mountaineering, Monte Rosa massif.

High mountains shows a fast response to global warming causing the acceleration in glacier shrinkage and permafrost degradation. In the Alps, this rapidly changing environment is often affecting mountain tourism.

Mountaineering is an important, iconic and highly structured activity. Its tourism chain can be simplified and categorised in four main locations: 1) access from valley bottom, 2) trails, 3) high mountain huts/bivouacs and 4) mountaineering routes. The augmented awareness of climate change effects on these locations is creating a favorable context for research development in the deep understanding of the threats for mountaineers and the support to stakeholders to establish long-term strategies for adaptation.

Many studies have been carried out about the effect of global warming on high mountain environments but only a few moved their attention to the consequences on mountaineering practice.

A PhD project in Earth Sciences has been approved at the University of Torino, whose aim is to assess the effect of climate change on mountaineering tourism. The area selected for investigation is the Monte Rosa Massif, in the Western Italian Alps, because of its historical interest in both environmental monitoring and mountaineering. The focus is on the Lys and Sesia basins, southern side of the massif, at an altitude range from 2800 m a.s.l. to the 4554 m a.s.l. of the Punta Gnifetti. The area includes two famous historical mountain observatories for environmental and physiology studies: 1) the Capanna Regina Margherita (top of Punta Gnifetti), the highest mountain hut in European Alps, inaugurated in 1893 as a scientific laboratory, and 2) the Angelo Mosso scientific Institute (sited at the Passo dei Salati, 3000 m a.s.l.), inaugurated in 1907. Both allows to retrieve long-term environmental data.

Mountaineering has its long history too in the Monte Rosa massif. In 1778, the first ascension took place at the “Roccia della Scoperta” (the discovery rock) by a group of local “adventurers”. Since then, mountaineering saw a continuous development with new ascents and routes becoming nowadays a founding pillar for mountain tourism. Many data are available on route descriptions, ascent reports, and hut attendance, collected since long time by mountain guide societies, hut keepers, local and national alpine clubs and municipalities. Data coming from both scientific and mountaineering sources will be collected and analysed at a massif scale approach, in order to create a “mountaineering sensitivity map” of the Monte Rosa, i.e. a map highlighting sectors of major influence of climate change on mountaineering practices. A further step will be the detailed investigation and in depth comprehension of climatic driving factors in “hotspot” identified within the study area.

## Gravity and magnetic data restoration with new processing and interpretation techniques

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During the past 60 years, the National Institute of Oceanography and Applied Geophysics (OGS) acquired a large number of gravity and magnetic data all over the Italian Peninsula and in the Mediterranean and Black seas. Thanks to the increasing computational power and the availability of many powerful software for data processing, it is today possible to extract new and more accurate information from the same datasets and merge them with the newest acquisitions. Data restoration is often a crucial factor for addressing new research projects and guide new scientific explorations. As a specific example, the hypothesis of the presence of several underwater volcanoes derived from the OGS gravity and magnetic acquisitions in the Sicilian Channel during the 70s have been substantially confirmed, and other volcanic edifices have been recently discovered a few tens of kilometres off the SW coast of Sicily during a geophysical cruise carried out by the R/V OGS Explora. This PhD project focused on restoring on-shore and off-shore gravity data from the OGS archives, addressing specific areas of interest: the Gulf of Manfredonia, the North Adriatic Sea, and the Friuli Venezia-Giulia region. The main target of these investigations is the identification of the subsurface fault networks lying below the Plio-Quaternary cover. Four different gravity datatypes were collected and merged to create the most detailed and homogeneous view of gravity anomalies in the study regions to date: (i) sea-bottom, (ii) sea surface, (iii) satellite altimeter, and (iv) land-based gravity. Processing all these different datatypes required a standard computational scheme to estimate topographic correction, draped-to-level upward continuation, and line levelling. In addition, the computation of topographic effects involved refining the available Digital Terrain Models (DTMs), covering both seafloors and continental areas. The analysis of the spectral content of the resulting gravity anomalies led to the interpretation of local density contrast, thorough the use of: (i) spectral and isostatic filtering for regional/local field separation, and (ii) combination of different potential field derivatives for data enhancement. In practice, the gravity data restoration and analysis helped to validate results of previous geophysical and/or geological interpretation and to gather new evidence of subsurface complexities in areas not yet covered by other geophysical and geological data.

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