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ABSTRACT BOOK

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COVER IMAGE

Interference fold patterns in mylonitic rocks (migmatitic paragneisses, leucocratic dykes, tonalites, and skarns) surfacing as a sea-stack (Palmi Shear Zone, Calabria – Italy; photo by Eugenio Fazio).

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Microtectonics

Visalli Roberto (University of Catania)

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Influence of deformation and fluids on Ti exchange innatural quartz

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Keywords: Quartz, TitaniQthermobarometry, correlative dataworkflow, geochemicalre-equilibration, cathodolumine-scence.

For over 10 years, the TitaniQ geothermometer has been used to constrain deformation temperatures in quartz-rich rocks. The calibration of the thermometer rests on the direct correlationof the titanium trace element concentration in quartz with respect to the ambient temperature. However, the processes and parameters which lead to re-equilibration of the Ti-in-quartz system during deformation are not yet fully understood. Here we analysed deformed quartz veins from theEastern Alps (Prijakt Nappe) applying a combination of microstructural, spectroscopic, and geochemical analyses. In contrast to recent studies which highlight the importance of strain, we show that the availability of free grain boundaries, fluids, and their partitioning play the dominant role in Ti resetting towards lower concentrations in our studied case of retrograde deformation. Weemploy a robust analytical approach to investigate the interplay between grain-scale deformation, fluid-rock interactions, and geochemical exchange during increasing strain in the quartz mylonites.With this approach, the microstructures representing most re-equilibrated sites for the application of the titanium-in-quartz geothermometer can be readily identified, even at lower greenschist faciesdeformation conditions and a recrystallization regime dominated by subgrain rotation.

These coarse-grained quartz veins, that formed at amphibolite facies conditions, were overprinted by lower greenschist facies deformation to different degrees. During the overprint, subgrain rotation recrystallization was dominant during progressive deformation to ultramyloniticstages. The initial [Ti] (3.0-4.7 ppm) and cathodoluminescence (CL) signature of the vein crystalsdecrease during deformation mainly depending on the availability of fluids across the microstructure. The amount of strain played a subordinate role in resetting to lower [Ti] and corresponding darker CL shades. Using a microstructurally-controlled analysis we find that the most complete re-equilibration in recrystallized aggregates ([Ti] of 0.2-0.6 pm) occurred (i) in strain shadows around quartz porphyroclasts, acting as fluid sinks, and (ii) in localized microshearzones that channelized fluid percolation. [Ti] resetting is mainly observed along wetted high angleboundaries (misorientation angle >10-15°), with partial [Ti] resetting observed along dry low angleboundaries (<10-15°). This study shows for the first time that pure subgrain rotation recrystallization in combination with dissolution-precipitation under retrograde condition provide microstructural domains suitable for the application of titanium-in-quartz geothermobarometry at deformation temperatures down to 300-350 °C.

Acknowledgements: This work is supported by the Deutsche Forschungsgemeinschaft DFG (BE 2413/3-1). The Oxford Instruments CMOS-Symmetry EBSD detector was funded by the DFG (JA 2718/3-1). GP acknowledge funding from the University of Padova (BIRD175145/17). Department of Earth Sciences "A. Desio", University of Milan, Via Mangiagalli 34, 20133, Milan.

Permian igh-temperature deformation in a pre-alpine continental crust: the case of the Valpelline Unit of the Austroalpine Domain (Western Alps, Italy)

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Keywords: high-temperature deformation, melt, Permian extension, pre-Alpine evolution, multiscale structural analysis.

High-temperature deformation and metamorphism provide key information about the evolution ofthe deep continental crust at different geodynamic contexts (i.e., extensional and compressional). Permian lithospheric extension is thought to be responsible for the high-temperature regime that affected the Variscan continental crust, nowadays fragmented and widespread worldwide, and within the Alpine belt. The subsequent Alpine high-pressure and low-temperature imprint, related to the subduction-collision event, has almost totally overprinted this extension-related HT metamorphism, leaving only small portions preserved. The Valpelline Unit (Dent-Blanche Tectonic System, Austroalpine Domain) is an example of those pre-Alpine Permian sectors of lower continental crust (i.e., high-grade gneiss, migmatite, amphibolite and marble; Pesenti et al., 2012; Manzotti & Zucali, 2013) that almost completely escaped the Alpine overprint. Granulite- facies rocks show complex meso- and microstructural patterns, which make difficult the reconstruction of the relative chronology of deformation events, due also to production, segregation and consumption of melt and HT diffusion creep recovery mechanisms (e.g., Nabarro-Herring creep; Knipe,1989; Passchier & Throw, 2005) which could erase traces of previous deformation mechanisms (Sawyer, 2001; 2008). Combining multiscale structural analysis (i.e., observation of overprinting relationships between different fabric elements) and discrete element modeling (DEM) this work aims at investigating the pre-Alpine high-temperature deformation of the Valpelline Unit rocks, focusing particularly on the migmatization processes which led to the production, migration of melt and its concentration in low strain domains (neck boudins, fold hinges, etc.). In particular, field observations have been compared to the results of simulations of melt migration during rock deformation in order to evaluate the parameters that affect this process. Understanding the parameters and mechanisms active during melt-present deformation and the resulting fabric relationships in these rocks is a solid base needed to address further studies (e.g., P-T-d paths; geochronology, partitioning of REE between melt and restite) on preserved pre-Alpinebasements which could provide new interpretations regarding the Permian HT tectonics affecting these deep continental fragments.

Acknowledgements: This workis supported bythe "ProDe – Progetto d'Eccellenza - Le geoscienze per la società: risorse e loro evoluzione - 2018-2022".

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Columnar calcite modification in high-pressure marbles: mechanism and implications

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Keywords: calcite microstructure, dynamic recrystallization, EBSD analysis, shear strain, Hellenides.

In orogens with abundant carbonate rocks (e.g., the Alpine-Himalayan belt), the structural evolution of high-pressure marbles as well as the microstructural evolution of calcite are very useful to understand the geological processes occurred within the subduction/exhumation channel. Columnar calcite that represents pseudomorphs after aragonite, was developed at peak metamorphic conditions (~350 °C) in the high-pressure marbles of the Basal Unit (Evia Island, Greece). The long axes and the c-axes of the columnar calcite grains were originally oriented normal to the foliation. Modification of the columnar microstructure by bending of the calcite long axes and/or dynamic recrystallization took place during the exhumation of the high-pressuremarbles. Based on the degree of modification of the columnar microstructure, the Basal unit wassubdivided into two main structural domains. In the East Domain, marbles were characterized by low to medium strain intensities associated with top-to-the-E shearing, whereas calcite was primarily deformed by subgrain rotation recrystallization. In the West Domain, marbles were affected by high to ultra-high strain intensities and calcite deformed dominantly by subgrain rotation recrystallization with a high contribution of bulging recrystallization. In the West Domain, deformation was localized in discrete shear zones mainly associated with top-to-the-E shearing.

In order to investigate the microstructural and textural modification of columnar calcite at increasing shear strain, we analyzed seven representative samples by means of electron backscatter diffraction (EBSD). The obliquity of the columnar calcite long axes with respect to the foliation was used to estimate the shear strain. The shear strain ranges from 0.1 to >3.7 and shows a strong linear correlation with the recrystallized area fraction. Calcite recrystallization commenced at very low shear strains (γ=0.1), whereas mylonitization (~60% area fraction of recrystallized grains) occurred at shear strains >3.7. Differential stress (10-32 MPa) and strain rate (10^{-14} - 10^{-13} s^{-1}) do not show any systematic variation with increasing shear strain. Texturalmodifications were minor with increasing shear strain, whereas shear strains >4 are possibly required to produce a new, strong CPO.

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Spatial and temporal stress change along a continental megathrust: case study across the Main Central Thrust in the Himalaya

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Keywords: strength profile, brittle-ductile transition, quartz mylonite, microstructure, texture.

What processes cause and regulate the interplay between fast and slow strain behaviour on faults? To tackle this question we investigate the internal deformational and thermal structure of an active continental megathrust exposing a full spectrum of active fault behaviours—from aseismic creep at depth to earthquakes creating surface ruptures. Himalayan thrusts havecollectively operated over broad ranges of pressure, temperature, and strain rates. As all these structures merge into the Himalayan basal décollement, the Main Himalayan thrust, it can be safely assumed that the rocks now at the surface were within the MHT at the time of their deformation.

We investigate the Himalayan megathrust system across a range of observation scales and approaches, including field observations, microanalyses, thermochronology, and numericalmodelling. We determined the metamorphic peak temperatures by Raman spectroscopy of carbonaceous material (RSCM) and established the deformation temperatures by Ti-in-quartz thermobarometry and quartz *c*-axis textures. These data were combined with thermochronology,including $^{40}Ar/^{39}Ar$ ages of muscovite, apatite fission-track ages, and apatite and zircon (U- Th)/He ages. To obtain accurate metamorphic, deformation and closure temperatures of thermochronological systems, pressures and cooling rates for the period of interest were derivedby inverse modelling of multiple thermochronological datasets, and temperatures were determined by iterative calculations (Grujic et al., 2020).

Microstructural and textural analyses of quartz mylonites from the Main Central thrust allow identification of switches of deformation mechanisms caused by reductions in pressure and temperature during exhumation, and they provide quantitative constraints on stress history. Ourpreliminary results indicate that the flow stresses at the peak deformation temperatures were thesame across the 4-km-wide shear zone but the strain rates decreased by two orders of magnitude from the core to the shear zone boundary. At the end of ductile shearing the flow stresses were on the order of 110 MPa. This allows us to calculate the conditions for frictional slip reactivationof the brittle, seismogenic part of the megathrust. At some localities there is an evolution of samples experiencing shifts to higher stress deformation that may be a result of interaction between end-member mechanisms where viscous flow cannot accommodate all the imposed displacement, which leads to "semi-brittle" deformation. The pulses of high stress might be associated with large earthquakes transferring stresses both up and downdip the megathrust.

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Folding of a single layer in an anisotropic viscous matrix under layer-parallel shortening

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Keywords: fold geometries, pure shear, anisotropy, strain localisation, axial-planar cleavage.

Folds are common structures in deformed rocks and give information on strain, rheology, kinematics, etc. While Biot's (1957) theory for fold formation applies to isotropic materials, rocks can have cleavages and foliations that make them intrinsically anisotropic in the rheology. The effect of that is not yet understood well, and is especially difficult to implement in modelling or numerical simulation. We here consider the effect of a mechanical anisotropy due to a foliated weak viscous matrix, for example by the of alignment of micas. Mechanical anisotropy can enhance shear localisation (Ran, et al., 2018; de Riese et al., 2019), resulting in low-strain microlithon domains and high-strain shear bands or cleavage domains. We investigate the fold geometries and strain-field differences resulting from moderate pure shear deformation, systematically varying the initial orientation of the mechanical anisotropy of the weak viscous matrix.

We use the Viscoplastic Full-Field Transform (VPFFT, Lebensohn & Rollett, 2020) crystal plasticity code coupled with the modelling platform ELLE (http://www.elle.ws; Piazolo et al., 2019) to simulate the deformation of a single isotropic layer embedded in an anisotropic power- law viscous matrix with an initial given lattice preferred orientation (LPO) as a proxy for the foliation as was done by Ran et al. (2018) and de Riese et al. (2019). Deformation is by pure shear, layer-parallel shortening.

The deformation behaviours, and hence fold geometry, depending on (1) the initial orientationsof LPO (α_0), (2) the viscosity contrast between the fold and matrix materials, (3) the magnitude ofanisotropy. Variation in these parameters results in different fold geometries ranging from foldingand thickening of the strong layer with the formation of new crenulation cleavages in the matrixto reduced thickening of the strong layer, larger fold wavelength and amplitudes and especially reorientation of the foliation without the formation of a new crenulation cleavage.

Our simulations not only reveal the finite strain geometry of the folds and foliations but also show the evolving distribution of the strain-rate field. We observe the formation of new axial planar crenulation cleavages at low α_0, and reorientation of the primary foliation towards the fold axial plane at high α_0. Furthermore, high α_0 cases cause formation of strain localisation together with lenticular microlithons on the scale of the fold wavelength.

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Crystallographic preferred orientation analysis of Cretaceous high pressure units of the Eastern Alps – preliminary results

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Keywords: CPO, EBSD.

The Saualpe-Koralpe high pressure (HP) complex as well as the HP units of the Pohorje mountains are part of the Eoalpine HP belt, which extends over about 350 km from west to east. It formed in conjunction with the Cretaceous orogenic cylce in the Eastern Alps and comprises eclogite lenses in a matrix of gneisses and micaschists. The eclogites were probably emplaced along the rift zone that led to the opening of the Meliata-Hallstatt ocean. After the closure of the ocean in the Jurassic, the former Adriatic margin entered an E-SE dipping subduction zone colliding with the microcontinent Trisia, which forms the South Alpine block today. Ongoing convergence led to underplating within the lower plate and the formation of the Austroalpine nappe stack. This finally led to eclogite facies conditions at 100-90 Ma. The Saualpe, Koralpe and Pohorje units reached peak pressure conditionsof2.2-2.4 GPa/630-690°C, 1.8-1.9 GPa/670°C and 3.0–3.7 GPa/710–940 °C, respectively. PT- analyses, microstructural investigations and dating predict different contrasting models for theexhumation of these units. Among these models are a Chemenda-type wedge extrusion, slab extraction as well as the exhumation through a low angle extensional fault.

Within our study we intend to unravel the deformational history of the Koralpe, Saualpe and Pohorje HP units during its exhumation. In a first step samples were taken in the Koralpe Complex in a 1 kmlong profile south of the Schirchleralm near Deutschlandsberg, Austria. The set includes two pristine eclogites, one fine grained and one coarse grained sample, a retrogressed eclogite as well as a gneisssample.

Crystallographic preferred orientation (CPO) analysis was performed with electron backscatterdiffraction (EBSD) at the transmission electron microscope of the Institute of Geosciences at the University of Cologne.

In the fine grained eclogite the <001> axis of omphacite shows an alignment in lineation direction while <010> is distributed within a girdle normal to the lineation with a maximum normal to the foliation plane. This indicates constrictional deformation. In the coarse grained eclogite the <001> axes show more of a girdle distribution with several maxima within the foliation plane, which could point to flattening strain. In the retrogressed eclogite hornblende <001> axes exhibit maxima in lineation direction with some distribution within the foliation plane while the <100> axes show maximanormal to the foliation plane. This indicates plain strain. In the retrogressed eclogite sample plagioclase also shows a pronounced CPO. Quartz {0001} axes in the gneiss sample show maximaatan angle to the foliation normal indication a top to the north-east sense of shear.

While the sample set is still too small to make large scale tectonic interpretations for the exhumationof the Koralpe Complex, they show a very variable and complicated deformational history of the rocks involved.

Origin and structural transformations of graphite in cataclasites from the Alpine Fault zone, New Zealand

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Keywords: graphite, formation, crystallinity, carbon isotopes, structural disorder.

Along the active Alpine Fault of New Zealand, the distribution of graphite was previously described across a strain gradient that increases with proximity to the fault. Throughout this entire hanging wall fault rock succession, graphite manifests itself as highly crystalline grains, reflecting metamorphic maturation. However, in the cataclasites graphite with lower degree of crystallinity wasalso encountered (Kirilova et al., 2017). One possible scenario is that this graphite formed by hydrothermal addition of carbonaceous material that had matured to a lesser degree. Alternatively, structural disorder of graphite due to deformation (Kirilova et al., 2018) may have affected the progressively matured metamorphic graphite. To identify the exact mechanisms that resulted in the coexistence of two structurally different types of graphite, we examine the origin and the structural transformations of graphite in these rocks.

We performed total organic carbon (TOC) and stable carbon isotope analyses on 3 samples representing the Alpine Schist, mylonite and cataclasite rocks. TOC measurements show graphite enrichment in a cataclasite sample (up to 2.74 wt.%) in comparison with analyzed schist and myloniterocks (≤ 0.52 wt.%). Carbon isotopic compositions of graphite range between -19.85‰ and -23.78‰ in the schist and mylonite samples, and between -26.32‰ and -28.64‰ in the cataclasite. These negative δ13C values suggest a biogenic origin of all graphite, and the distinct negative shift of δ13Cvalues in the cataclasite is attributed to fractionation effects. We speculate that fluids derived from the schist and/or mylonite succession resulted in hydrothermal addition of less crystalline graphite. However, scanning electron microscopy images reveal graphite is concentrated within strained areas (Kirilova et al., 2017) suggesting that its final structural order may be partially a result of modificationby deformation after its deposition. We employ transmission electron microscopy (TEM) on cataclasites to reveal the microstructural characteristics of this graphite. TEM data show that graphitehas been locally deformed during which its crystalline structure would have been further reduced.

We conclude that the structural transformation of graphite in the Alpine Fault cataclasites results from a combination of chemical (hydrothermal precipitation) and mechanical processes (concentration and structural modification of graphite in strained areas). The documented graphite enrichment may also be sufficient to facilitate fault motion.

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Stylolites in carbonate rocks: morphological variations according to host rock textures

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Keywords: stylolites, lithofacies, statistics, distribution.

Sylolites are ubiquitous structures in carbonate rocks that show roughness varying from very smooth to extremely serrated. They can present a dual behaviour in terms of fluid circulation, acting either as conduits or baffles for fluid flow. Recent studies have shown that this behaviour can be intimately related to the variation of their morphology, which is strongly influenced by the texture of the host rock (Humphrey et al., 2020; Gomez-Rivas et al., 2022). Despite there are several studies dealing with the link between the length and space (i.e., aperture) there is a lack of a systematic quantitative data about the relationships between stylolite morphological parameters and carbonate host rock textures. To fill this gap, we characterize the most important stylolite morphological parameters, including length, aperture, filling material, spacing and connectivity, for a wide variety of carbonate textures and lithofacies. This analysis is based on the stylolite classification of Koehn et al. (2016) and the carbonaterock textures of Dunham (1962). We have analyzed about 50 thin sections of carbonate rocks from different settings. The results reveal that some parameters such as stylolite length and aperture, or shapes and linearity are related between them and are also strongly affected by the host rock characteristics like grain size. In this regard, there is a slight increase of stylolite index of linearity(ratio between straight and real length) from mud-dominated (mudstones and wackestones) to grain- dominated textures (packstones to grainstones), while stylolite aperture distribution shows a negative trend towards grainstones. The highest stylolite aperture is observed for seismogram type stylolites, which are abundant in packstones, while the lowest one corresponds to suture and sharp peak stylolites that are dominant in wackestones. In addition, as was expected, wave-like type stylolites show the highest linearity and this is progressively reducing towards suture-sharp peak, seismogram and rectangular ones that has the lowest values. Moreover, the stylolites in mud-dominated textures showthe highest amount of filling parts along their surface respect to the ones in the grain-dominated ones.

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Nanostructures in Oriented Thin Films – From Microtectonics to Nanotectonics and Nanokinematics in Deformed Rocks

Mamtani M.A.*[1], Kontny A.[2], Hilgers C.[2], Reznik B.[2], Wenzel O.[3], Müller E.[3], Störmer H.[3] & Renjith A.R.[4]

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Keywords: microtectonics, nanotectonics, magnetite, SEM-EBSD, TEM, deformation mechanism, nanokinematics.

A critical aspect of microtectonic studies is that the investigations are done in oriented rock thin sections, typically in the kinematic reference frame (XZ of the strain ellipsoid, i.e., section parallel to the stretching lineation and perpendicular to the foliation). In this study we present nanostructures in oriented thin films excavated from rock thin sections that were prepared parallel to XZ section. Results from two studies involving oriented thin film excavation (using Focused Ion Beam, FIB) of magnetite, followed by nanostructure observation under TEM are discussed. In both the cases, SEM-EBSD data of magnetite is used to identify region of interest (ROI) for FIB lamella (thin film) excavation.

The first study is of magnetite hosted in mylonitized mica schist (Slipsiken, Sweden), in which two "*plane normal*" thin films are extracted, one each across low angle grain boundary (LAGB; 6º misorientation) and high angle grain boundary (HAGB; 26º misorientation). TEM investigation established presence of translational and rotational Moiré fringes, respectively, across LAGB and HAGB. Dislocations, slip bands, stacking faults, twins and recrystallized domains were observed in the vicinity of the grain boundaries, thus providing unequivocal evidence ofintracrystalline deformation of magnetite. The sense of shear in the oriented rock thin section was dextral, which in the geographic reference frame is top-to-NW. The rotational component inferred from the Moiré fringes recorded at the nanoscale complements the dextral shearing. Thus, the nanotectonics deciphered fromTEM studies supports regional tectonics (Mamtani et al., 2020).

The second study is of magnetite in Banded Iron Formation (BIF) from Norway, in which two "in plane" thin films (lamella L1 and L2) were excavated. This allows observation of nanostructures in the kinematic reference frame (XZ of the strain ellipsoid) for the first time in geosciences. LAGB-1 and LAGB-2,3 were respectively identified inL1 and L2 under TEM. The angle (θ) between LAGB and the elongation (X) direction of the strain ellipsoid, shear strain (γ) and dislocation density (ρ) for each LAGB are calculated. Our study revealed that (a) $\theta_{LAGB-1} < \theta_{LAGB-3} < \theta_{LAGB-2}$, (b) $\gamma_{LAGB-1} > \gamma_{LAGB-3} > \gamma_{LAGB-2}$, and (c) $\rho_{LAGB-1} > \rho_{LAGB-3} > \rho_{LAGB-2}$. Thus, it is concluded that, empirically, lower the angle between LAGB and X-direction, the higher are the shear strain and dislocation density along that LAGB. This "nanokinematics" is in-sync with the microscale dextral kinematics in the BIF thin section, which is confirmed from quartz CPO using SEM-EBSD analysis.

We propose that the present approach of TEM imaging of nanostructures in oriented thin films excavated parallel to the kinematic reference frame maybe referred to as "*nanokinematics*". We envisagethat this approach opens up a new avenue of research in geosciences, i.e., TEM investigation of orientedthin films (lamellae) of minerals. The obtained nanoscale structural information can enable multiscale investigation of atomic defects in minerals in the kinematic reference frame, thus providing useful information for forward modelling of ductile to brittle failure in deformed rocks.

Acknowledgments: The authors acknowledge funding from the DAAD and Alexander von Humboldt Foundation (Germany).

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The Simplon Shear Zone (Western Alps): how middle and upper continental crust reacts to prolonged extension

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Keywords: Simplon Shear Zone, vorticity, Ar/Ar geochronology, paleopiezometry.

The crustal scale low-angle normal faults are structures commonly active at mid to upper crustal levels within quartz- and feldspar-rich rocks and in orogenic post-collisional setting promote the exhumation of deep-seated rocks. PT conditions, differential stress, pore fluid pressure and time duration of activityare all factors that could significantly operate on how a shear zones develops in space and time. Therefore, the understanding of mechanisms controlling their development could provide invaluable insights on the rheology of the continental lithosphere.

We investigated the evolution of the Simplon Shear Zone (SSZ, Western Alps) formed as an extensional detachment accommodating E-W directed lateral extrusion after the collision between Adrian and European plates. Several tens of kilometres of extension were accommodated by the Simplon Shear Zone, allowing the exhumation of the deepest portions of the Western Alps.

By means of a quantitative approach we studied the evolution of the Simplon Shear Zone constraining the meso-, microstructures and vorticity distribution across the shear zone, its time of activity by $^{40}Ar/^{39}Ar$ dating of syn-shearing micas and its correlation with simple shear component distribution, theestimates of magnitude and variation of differential flow stress and strain rates during shear zone evolution obtained through EBSD-assisted quantitative microstructural analysis. All these data have been combined to reconstruct the temporal and structural evolution of the shear zone as the result of therheological response of involved rocks to changing PT and stress conditions.

The Simplon Shear Zone evolved from epidote-amphibolite to greenschist facies and then brittle conditions during shearing. A decrease of simple shear component from c. 90% to c. 40% towards the top of the shear zone is observed, with mylonites displaying ages of 12-8 Ma. Calculated differential stress (59-78 MPa) and strain rate (10^{-11}-10^{-12} s^{-1}) are in agreement with values of several other crustal-scale low-angle normal faults developed at medium to shallow crustal levels.

Our approach used at different scales revealed that the Simplon Shear Zone experienced a complexevolution, with shear strain that was heterogeneously distributed across the fault zone. Even though this heterogeneity, a general decrease of the simple shear component and increase of the differential flow stress toward the top of the shear zone is clearly defined.

Microstructures superposition in marble mylonites: atool to infer the progressive deformation of the SouthTibetan Detachment System in Himalaya

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Keywords: Calcite fabric, differential stress, twinning, rheology, Himalaya.

The low competence contrast between rheological domains in homogeneous marble mylonitemakes it difficult to distinguish, at a first glance, those kinematic indicators typically used to characterize a shear zone. Nevertheless, the observation of calcite microstructures is promising in understanding the deformation regime at a small scale, to infer more regional information (Molli & Heilbronner, 1999; Spanos et al., 2015; Negrini et al., 2018). In this contribution, we focus on calcite microstructures and their superimposition to constrain the deformation style ofa regional-scale shear zone, the South Tibetan Detachment System (STDS) in the Manaslu area of central Himalaya (Western Nepal). Here, carbonate rocks are the main lithotypes cropping outwithin over 1 km-thick mylonitic zone, where a top-down-to-the-north sense of shear is mainly defined by asymmetric folds, rare asymmetric porphyroclasts, and oblique foliations. We combined calcite grain size, twins, crystallographic preferred orientations (CPOs) data, and petrographic observations to define the contribution and timing of two main deformation mechanisms in calcite: grain boundary mobility and twinning. Calcite CPOs highlighted that both mechanisms were active during the STDS shearing. By comparing deformation temperature, differential stress, strain rates, and kinematic vorticity results, we defined differentdeformation conditions at which grain boundary mobility and twinning were dominating on eachother, testifying to a progressive shallowing of the detachment. Ductile deformation evolved from deeper to shallow crustal levels, where decreasing temperatures and increasing differentialstress produced strain hardening still under ductile regime. This contribution highlights how marble rheology influenced, on a regional scale, the exhumations along a low-angle shear zone from the middle to the upper crust.

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The role that mylonitic rocks play in the kinematic reconstruction of the western Mediterranean microplates

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Keywords: 2.0 microstructural analysis, vorticity analysis, strain rate, Mediterranean geodynamics.

Since the insight work of Wise et al. (1984), who classified the dynamics of fault-related rocks according to the competition between strain rate and rate of recovery, mylonitic rocks have become increasingly central in the reconstruction of plate kinematics, representing *de facto* a snapshot of Earth dynamics.

This dynamic view suggests that the evolution of basement units' can be interpreted as being the result of the strain state level, wherein the lower strained domains mostly preserve the earlier metamorphic assemblages. The mylonitic domains are generally developed at the contact with other basement units or at the edges of microplates, and show gradual replacement of older metamorphic growth sequences, linked to previous planar/linear fabrics, by the latest mineralogicalre-equilibration, often characterized by strongly deformed fabrics.

The strain analysis of mylonitic rocks can be considered a challenging role to interpret the reconstruction of microplate kinematics. Recently, a purely geometrical analytical approach was integrated with an infinitesimal one, by several empirical paleo-piezometers based on the progressive changing in space and time of the: a) Rheological properties; b) Strain Temperature; c)Lithostatic and deviatoric stress field; d) Mineral grain size of pre- and syn-kinematic rock constituents; d) Fluid availability, involving basement rocks.

In this interpretation, the articulated geodynamics of the western Mediterranean realm, characterized since the late Paleozoic by the formation of mutually interacting microplates, result in an amazing 'gaming table' where the vorticity analysis and strain-rate estimation of differently aged mylonitic horizons are able to more reliably constrain past tectonics.

The Calabrian Peloritani Orogen (CPO), for instance, represents a piece of the original southern European Variscan palaeomargin, which originated as a result of the Late-Paleozoic dextral transpressive activity of the Eastern Variscan Shear Zone (EVSZ) (Ortolano et al., 2022). It then drifted due to the Meso-Alpine dextral strike-slip tectonics which accompanied the Sardinian- Corsica Block in the present-day position (Ortolano et al., 2020), and this was followed by the Oligocene-Miocene stacking activity, which drives the exhumation and drifting of the CPO to the present-day geodynamic position (Cirrincione et al., 2015).

In order to obtain more objective and statistically meaningful fabric parameters for vorticity analysis and paleo-piezometry purposes, a 2.0 microstructural analytical approach (Visalli et al., 2021) is applied for the quantitative extrapolation of grain-size/-shape distribution analysis, subdivided per mineral type (Ortolano et al., 2020). This ultimately enables us to better constrainthe CPO geodynamics from late-Paleozoic up to the early-Miocene.

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The role of fault rock fabric in the dynamics of laboratory faults

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Keywords: frictional stability, fault fabric, microstructures, faults, rock mechanics.

Fault stability is inherently linked to the frictional and healing properties of fault rocks and associated fabrics. Their complex interaction controls how the stored elastic energy is dissipated,

i.e. through creep or seismic motion. In this work we focus on the relevance of fault fabrics in controlling the reactivation and slip behaviour of dolomite-anhydrite analogue faults. We designed a set of laboratory experiments where we firstly develop fault rocks characterized by different grain-size reduction and localization at normal stresses of 15, 35, 60 and 100 MPa and secondly, we reload and reactivate these fault rocks at the frictional stability transition, achieved at normal stress of 35 MPa by reducing the machine stiffness. When the normal stress is reduced, reactivation occurs with relatively large stress drops and large peak-slip velocities. Subsequent unstable behaviour produces slow stick-slip events with low stress drop and with either asymmetric or gaussian slip velocity function depending on the inherited fault fabric. When the normal stress is raised, deformation is accommodated within angular cataclasites promoting stable slip. The integration of microstructural data (showing brittle reworking of pre-existing textures) with mechanical data (documenting restrengthening and dilation upon reactivation) suggests that frictional and chemical healing can be a relevant process in developing large instabilities. We infer that chemical and frictional healing, which is common in natural faults during the interseismic phase, facilitates unstable reactivation. We also conclude that fault rock heterogeneity (fault fabric) modulates the slip velocity function and thus the dynamics of repeating stick-slip cycles.

Development of regional-scale shear zones revealed by multidisciplinary investigation: the case study of the Ferriere-Mollières Shear Zone (Argentera Massif, Western Alps)

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Keywords: transpression, vorticity, Quartz fabric, Monazite petrochronology, palaeopiezometry.

Shear zone behavior is mainly controlled by deformation regime (brittle versus ductile), deformation temperature, strain rate and magnitude, and rheology of the deformed rocks. If a gradient of strain is established across a shear zone, softening phenomena can cause a progressivelocalization of deformation in its core, resulting in a constant thickness shear zone with increasingstrain. In contrast, strain hardening may induce migration of deformation into the wall-rocks, causing an increase in shear zone thickness. In the Western Alps we have studied a NW-SE striking steeply dipping km-scale shear zone, the Ferriere-Mollières Shear Zone (FMSZ), that cross-cuts Variscan migmatites in the Argentera External Crystalline Massif. The shear zone is characterized by a deformation gradient (Carosi et al., 2016), with strain increasing toward the center of the shear zone which we interpret to be associated with strain softening during Variscan retrograde metamorphism. By combining structural and microstructural analyses with quartz fabric analysis, quartz palaeopiezometry and petrochronology, three main stages of shear zone development are recognized (Simonetti et al., 2021). Each stage is characterized by specific age, temperature and deformation regime. Stage I occurred between ~340 Ma and ~330 Ma under a temperature range of ~610 - 590 ◦C with a prevalent (76%–65%) component of pure shear deformation; stage II occurred between ~ 330 and 320 Ma at temperatures between ~ 530 and 480°C with a decrease in the component of pure shear (73%–49%); stage III developed from ~320 to 300 Ma under temperature conditions between ~ 500 and 420°C with a prevalentcomponent of simple shear (pure shear of 39%– 31%).

The FMSZ is a new example of a strain-softening and long-lasting regional-scale shear zone, useful as a natural study area for future research on processes operating in large-scale shearzones.

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Frictional control on the base of the seismogenic zone: insights from the Apenninic basement, Central Italy

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Keywords: earthquakes, rheology, friction, structural heterogeneities, basement, seismogenic regime.

Crustal seismicity is in general confined within the seismogenic layer, which is bounded, at depth, by processes related to the brittle-ductile transition (BDT) and in the shallow region by fault zone consolidation state. In the last 10-15 years, high resolution seismological and geodetic data have shown that faulting within the seismogenic layer occursin a large variety of slip modes. Frictional and structural heterogeneities have been invoked to explain such differences in fault slip mode and behaviour. However, an integrated and comprehensive picture remains extremely challenging because of difficulties to properly characterize fault rocks at seismogenic depths. This is not the case of the active region of central-northern Apennines, where the integration of deep-borehole stratigraphy and seismic reflection profiles with high resolution seismological data show that the strongest seismic sequences are limited within the sedimentary cover (depth < 9-10 km), suggesting that the underlaying basement plays a key-role in dictating the lower boundary of the seismogenic zone. Here we integrate structural data on exhumed outcrops of basement rocks with laboratory friction data to shed light on the mechanics of the Apenninic basement. Structural data highlight heterogeneous and pervasive deformation where foliated and phyllosilicate-rich rocks surround more competent quartz-rich lenses up to hundreds of meters in thickness. Phyllosilicate horizons deform predominantly by folding and foliation-parallel frictional sliding whereas quartz-rich lenses are characterized by brittle signatures represented by extensive fracturing and minor faulting. Laboratory experiments revealed that quartz-rich lithologies have relatively high friction, $\mu \sim 0.51$, velocity-strengthening to neutral behaviour, and elevated healing rates. On the contrary, phyllosilicate-rich (muscovite and chlorite) lithologies show low friction, $0.23 < \mu < 0.31$, a marked velocity strengthening behaviour that increases with increasing sliding velocity and negligible rates of frictional healing. Our integrated approach suggests that in the Apenninic basement, deformation occurs along shear zones distributed on thickness up-to several kilometers, where the frictionally stable, foliated, and phyllosilicate-rich horizons favour aseismic deformation and therefore confine the depth of major earthquake ruptures and the seismogenic zone.

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Complex recrystallization history of quartz at deep subduction levels: examples from Hellenides (Greece)

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Keywords: Quartz recrystallization; grain-size statistics; differential stress; columnar calcite; exhumation channel.

In this work, we present the complex recrystallization history of quartz occurred at nearly peak conditions to early stages of exhumation of high-pressure metamorphic units. We studied quartz-rich samples collected from different structural levels of the 1.5 to 2.0 km thick Phyllite-Quartzite unit (Peloponnese, Greece), and from the hanging-wall of two major shear zones in the Blueschist Unit (Cyclades, Greece). In both units, we observed, in thin-section scale, the whole spectrum of recrystallization mechanisms from grain-boundary migration (GBM) to bulging (BLG). The quartz wasmainly recrystallized within the subgrain-rotation (SGR) field and is characterized by a large variation in recrystallized grain size.

In both units, GBM was active in quartz at peak conditions (~500°C). Ductile deformation mainly occurred at the early stages of exhumation, at temperatures 500-450°C, where quartz recrystallization took place from the GBM/SGR to the SGR/BLG transition. Statistical analysis ofquartz recrystallized grain size distributions in the Phyllite-Quartzite unit, revealed that the SGR recrystallization was related to the formation of two, and locally three, clusters of recrystallized quartz grain size. The bi- and tri-modal distributions of quartz grain size may reflect episodic increase in differential stress (Kidder et al., 2016). Using quartz recrystallized grain size piezometry, we estimated that the differential stress in the quartz-rich lithologies episodically increased from 17 MPa to 31 MPa throughout the unit. This stress increase resulted in an increasein strain rate of, at least, one order of magnitude (from 10^{-13} to 10^{-12} s^{-1}). We interpret the stress andstrain rate increase to have taken place at the early stages of exhumation and likely lasted less than 0.5 Myr. Stress increase was followed by stress drop as indicated by partial foam microstructures of quartz. In the Blueschist Unit, grain size distributions are strongly asymmetric towards the smaller grain sizes and yielded a maximum differential stress of 55 MPa. A temporal increase in strain rate of two orders of magnitude (from ~10^{-12} to ~10^{-10} s^{-1}) is inferred to have occurred at constant deformation temperatures, during the formation of the shear zones at the early stages of exhumation. Well-preserved calcite pseudomorphs after aragonite within the marbles within the footwall of the studied shear zones indicate that ductile shearing, and consequently, quartzrecrystallization, ceased at blueschist facies conditions and temperatures greater than 400°C.

Summarizing, it seems that the transition from GBM/SGR to SGR/BLG recrystallization inquartz, and the formation of different generations of recrystallized quartz clusters within the same recrystallization field (SGR) occurred in a short period of <0.5Myr and is linked with an increase in strain rate of, at least, one order of magnitude. Our results suggest that ductile deformation in subduction zones may be episodic and reflect pulses of increased stress and strain rate.

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S2.

Active tectonics: local/regional observations and monitoring methods

CONVENERS & CHAIRPERSONS

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Active tectonic deformation along the Alfeo-Etna Fault System (western Ionian Sea)

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Keywords: Ionian Sea; earthquakes, bathymetric data, seismic reflection data; GNSS data.

On April 15, 2022, an earthquake with M=4.2 occurred at a depth of 30 km in the western Ionian Sea, about 39 km off the coast between Catania and Siracusa. It was the mainshock of a sequence thathas affected this sector of Ionian Sea since November 2021. Seismic profiles and bathymetric maps, as well as seismological data (Gambino et al., 2022), suggest that the seismogenetic volume is characterized by the occurrence of the northern branch of the Alfeo-Etna Fault System (Polonia et al.,2016; the North Alfeo Fault, Gutscher et al., 2016), a large NW-SE trending dextral shear zone that stretches from the southeastern slope of Mt. Etna to the Alfeo sea mount. According to morpho- structural and marine data, the Alfeo-Etna Fault System turns to N-S direction approaching the Ioniancoastline, where the extensional Timpe Fault System is mapped. In turn, NW-SE trending right-lateralstrike-slip faults connect the Timpe Fault System with the Etna volcano's upper slope, where eruptiveactivity primarily occurs along N-S to NE-SW trending fissures. Morpho-structural analysis, combinedwith geodetic and seismological data, suggests that the shear zone on the volcano's eastern flank and the Ionian offshore have similar transtensional features. Fault systems are related to ~ NNW–SSE horizontal P-axes and local ~E-W trending extension and they are seismically active having given riseto events with magnitude mostly between 1 and 4 and hypocentral depth ranging from 10 to 25 km inthe offshore and at shallower depths in the eastern flank of Mt. Etna. The Alfeo-Etna Fault System, which probably accommodates differential motion of adjacent western Ionian compartments via rightlateral kinematics, is a major kinematic boundary in the western Ionian Sea associated with the Africa-Europe plate convergence. The recent occurrence of earthquakes with magnitude greater than 4 suggests that a better assessment of geological hazard in this area is required.

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Structural assessment of Mt. Etna from twenty-five years of SAR interferometry

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Keywords: Etna, SAR.

From the first applications (e.g., Massonet et al., 1995; Biggs et al., 2014), the Synthetic Aperture Radar (SAR) interferometry is largely proved to measure ground deformations at the scale of the volcanoes with space and time resolution suitable to monitor the dynamic induced by the volcanic activity and to assess dynamics and geometry of their active tectonic features. Particularly fruitful for the structural studies are the techniques based on the interferometric analysis of time series of SAR passes for two main reasons: fist, because the time series analysis allows reducing or removing the most common atmospheric or geometric artefacts in the SAR interferometric images and second, because long lasting subtle deformations along faults are optimally defined (Ferretti et al, 2001; Lanari et al., 2007). Mt. Etna was one of the first volcanoes in which SAR was used for structural studies (Borgia et al., 2000; Bonforte et al, 2011). In this presentation, the results of twenty-five years of interferometric SAR analysis is presented and discussed to update the earlier studies with the twofold aims: to confirm, detailor modify the structural assessment of the active features of the volcano and to evaluate the possible effects of the volcanic activity on the dynamic of the structural features. To this aim, we will use the information from the velocity fields measured at different time windows.

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Late Miocene - Recent evolution of the Squillace Basin (Offshore Calabria, Italy): a multiscale approach to detect seismogenic faults

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Keywords: active tectonics, Calabrian Arc, multiscale analysis.

We have reconstructed the tectono-stratigraphic architecture of the Squillace Basin (Ionian offshore of the Calabria region) from the Late Miocene to Recent, and distinguished between shallow, non-seismogenic, active faults, and deep blind faults, capable of producing large earthquakes. We have used a multiscale approach based on the interpretation of seismic reflection profiles with different penetration/resolution, calibrated with well-log data and integrated with bathymetric data, and the distribution of instrumental earthquakes.

Our results highlight the occurrence of three main tectonic events. The first extensional/transtensional phase occurred during the Late Miocene. This event led to theformation of roughly W-E oriented horst and half-graben structures and a WNW-ESE transtensional fault located in the central sector of the basin. During the Pliocene, the extensional/transtensional tectonics continued to be dominant. From the Early Pleistocene(Calabrian), the extensional tectonics was interrupted by a left-lateral transpressional phase. This last event caused the positive inversion of some deep (> 3 km) extensional faults inherited from the previous event and the formation of NW-SE to WNW-ESE transpressional/thrust faults and related anticlines. The latter deform the seafloor of the northern and western basin, forming NW-SE to WNW-ESE oriented ridges. These transpressional structures can be considered the offshore prolongation of the transpressional faults formed in the left-lateral shear zones documented in the northern Calabrian Arc.

At the culmination of anticlines related to the deep transpressional faults, shallow (<3 km) high-angle normal faults offset the younger deposits. Some of the faults propagate upwards reaching the seafloor and forming well-developed seabed scarps. These morphological features indicate the recent fault activity. The orientation of the shallow normal faults is parallel to the elongated axis of the ridges. Based on their depth and direction, we interpret these faults as secondary structures due to tensional stress that occurred in the extrados of the anticlines associated with the transpressional structures.

Our findings are supported by seismological data. The earthquake location highlights severalalignments that reveal active structures affecting the Ionian offshore, oriented around NW-SE. Events are mainly located in the northern sector of the Squillace Basin, with a depth range between 0 and 30 km. Focal mechanisms of earthquakes with M> 3 indicate mainly strike-slip or transpressive movements.

Active tectonics controls the dynamics of the Atlantic- Mediterranean divide in the western Betics (S Spain)

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Keywords: post-Tortonian uplift, Atlantic-Mediterranean watershed, endorheic basins, transpression, southern Iberia.

The Atlantic-Mediterranean main water divide in the Guadalhorce sector of the Betics(southern Spain) is highly unstable since the upper Miocene. In contrast with the central sector of the chain, where it is located at the internal zones, the Atlantic-Mediterranean divide in this sector is a broad, diffuse, low-lying area at the fold-and-thrust belt, with complex relationships between several hm to km-scale endorheic basins and low energetic, Atlantic and Mediterraneanrivers. This endorheic-dominated area is limited by two km-scale, ENE-WSW striking, dextral transpressional zones: the Algodonales-Badolatosa shear zone (ABSZ) to the north and the Torcal shear zone (TSZ) to the south. Recent deformation at these shear zones and other minor structures in the endorheic-dominated sector affects Tortonian-Quaternary rock units, producingtectonic uplifting.

Tortonian-Messinian shallow marine sedimentary units show different altitudes (350-800 m a.s.l.) that can be attributed to differential uplifting. Maximum altitude differences, between some areas of the TSZ and the lowermost altitudes at the endorheic-dominated area, reach 450 m. The possible contribution of post-Tortonian transpression at the TSZ to differential uplift is evaluated by kinematic modelling, using the kinematic parameters assigned to this zone by Díaz- Azpiroz et al. (2014) in the equation $U(dt) = z(t_0)$ [sin δ exp($\dot{\varepsilon}$t) − 1], where $U(dt)$ is the total differential uplift, $z(t_0)$ is the depth of the detachment level of the transpression zone (4500-6000 m), δ is the dip angle of the zone (73º), $\dot{\varepsilon}$ is the pure shear strain rate (3.2-7.4 $\cdot$ 10^{-16} s^{-1}) and *t* is the time deformation has been active (the last 7.3 my, since the Tortonian-Messinian boundary). The total contraction *(e)* produced at the TSZ in this time would thus be 0.07-0.17. Our theoretical results range between 167-868 m, but the observed altitude differences in the study area are better reproduced by our model considering a total contraction *(e)* value between 0.09 and 0.11. These results suggest that the differential post-Tortonian uplift between the TSZ and surrounding areas can be attributed completely to transpression at this shear zone.

Our structural, geomorphic, hydrogeological and sedimentological data indicate that differential uplifting in the study area exerts a great control on the Atlantic and Mediterranean rivers dynamics as well as the endorheic divides reorganization. Tectonic uplift at the ABSZ andTSZ lowers rivers' erosional power, thus preventing the capture of endorheic basins. By contrast,new endorheic basins are nucleated and existing ones are re-shaped or eventually captured due to the activity of discrete structures. In conclusion, active tectonics plays a main role on the instability of the Atlantic-Mediterranean water divide in this sector of the Betic chain.

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3D modelling of Quaternary faults in Southern Calabria

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Keywords: active tectonic, seismogenic faults, Calabria, 3d modelling.

A multidisciplinary analysis was carried out in southern Calabria to define, through a 3D analytical model, the geometry, kinematics and dynamics of the main Quaternary tectonic structures slicing across the area. Some of these fault structures (e.g., Serre, Cittanova, S. Eufemia and Scilla faults; Jacques et al., 2001) are thought to be the seismogenic sources of the 1783 seismic sequence (M 6.5-7). The geometry of the Cittanova fault plane, as well as the related strain-stress field, was determined using the distribution of crustal seismicity projected on a schematic geological section, reconstructed through the interpretation of CROP seismic profiles (M-2B and M2-A/III; Finetti, 2005), and morpho-structural investigations. Modelling isperformed through the MOVE software's 3D kinematic tools, and the TDE (Triangular Dislocation Elements) analytical method (Meade, 2007). The geometric, seismological and kinematic properties of the modelled fault have been validated by comparing results to empiricalmodels (e.g., Wells & Coppersmith 1994, Manighetti et al., 2001). These results and methods are applicable to the kinematic inversion of available GNSS geodetic data with the GAME software (Cannavò, 2019) and may be used to study other active tectonic structures in the southern Calabria area.

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GNSS monitoring of Belpasso-Ognina Fault, the southern boundary of Mt. Etna unstable flank

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Keywords: GNSS monitoring, Mt. Etna Eastern flank, Belpasso-Ognina Fault.

The Belpasso-Ognina Fault extends for almost 20 km along the southern flank of Mt. Etna. This structural alignment does not show topographic evidence indeed it was detected using InSAR interferometric technique (Froger et al., 2001), lately implemented using PS InSAR technique (Bonforte et al., 2011). We present the results of a GNSS monitoring, performed for the first time along the Belpasso-Ognina structural lineament. The network, composed by 6 benchmarks, was realized after a detailed study about geometric e geological parameters of the fault; monitoring campaigns have been carried out from December 2018 to March 2020, every 2-3 months in static mode, with 8 hours of acquisition time. In post-processing we computed the velocity field in a fixed Hyblean reference frame. Results show the trend of movement of the Belpasso-Ognina Fault towardseastern sectors, which is consistent with the motion of the entire Mt. Etna eastern flank (Froger et al., 2001; Bonforte et al., 2011,2012; Mattia et al., 2015; De Guidi et al., 2018). Ps InSAR analysis carriedout from 1995 to 2000, (Bonforte et al., 2012) shows that Belpasso-Ognina Fault is characterized byan abrupt velocity variation in the southeastern sector where it interrupts the high rate of uplift of almost 5-10 mm/years, related to the Catania Anticline (De Guidi et al., 2015). The monitoring of Belpasso-Ognina Fault within the volcano-tectonic context of Mt. Etna, confirms that it plays the roleof southern boundary of the Mt Etna unstable flank (see also Bonforte et al., 2012).

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Speleothems as recorder of active tectonics: Do they break or not?

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Keywords: earthquake geology, speleothem, active tectonics, paleoseismology, Dodecanese.

Broken speleothems have been used as indicators for paleo-earthquakes although a direct link between earthquake and damage in caves is difficult to prove and only few reports describe processes in caves during recent earthquakes. Besides damage related to offset along faults, which is not necessarily a proof of seismicity, there is a debate if earthquake ground motions can cause resonance of long and thin stalactites and stalagmites resulting in failure (*e.g.* Mendecki & Szczygieł, 2019).

We mapped before and after the 2017 Mw 6.6 Bodrum–Kos earthquake the so-far unexplored Korakia Cave on Pserimos island in the Dodecanese (Greece), which is located at the transition between the Aegean and Anatolian region, historically known for its strong seismicity (Grasemann et al., 2022). The cave formed along an active normal fault and records numerous fault-related broken columns and flowstones sealed by younger speleothems. New ^{230}Th/U-ages show that displacement along the fault occurred since the formation of the cave, which is older than the limit of the dating method. Interestingly, hundreds of long and thin stalactites and stalagmites, with length-to-width ratio larger than 10, are undamaged. However, our dating shows that some of them must have experienced strong historical earthquakes including the nearby 161 ka Kos-Plateau-Tuff eruption and caldera collapse, which was the largest Quaternary eruption in the Aegean region.

During a cave visit after the 2017 M_W 6.6 Bodrum–Kos earthquake, which also caused the collapse of several buildings on the island of Kos only 4 km S of Pserimos, we noted that c. 10 cm small stalactites, which were actively growing along fractures in the cave ceiling, have beenchipped off by movements along the fractures. Therefore, earthquake ground motion was capable of causing small shear displacements on open fractures causing damage of stalactites. We conclude that stalactites and stalagmites are difficult to break by oscillation and resonance effects, but seismic and aseismic displacement along faults can easily break speleothems.

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The FOCUS project: monitoring a submarine strike-slip fault, using a fiber optic strain cable, seafloor geodesy and a land-sea seismological network

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Keywords: strike-slip fault, fiber optics, seafloor geodesy, monitoring, seismological network.

The goal of the ERC (European Research Council) funded project - FOCUS is to apply laser reflectometry on submarine fiber optic cables to detect deformation at the seafloor in real time using BOTDR (Brillouin Optical Time Domain Reflectometry). This technique is commonly used monitoring large- scale engineering infrastructures (e.g. - bridges, dams, pipelines, etc.) and can measure very small strains (<< 1 mm/m) at very large distances (10 - 200 km), but until now has never been used to studytectonic faults and deformation on the seafloor.

Here, we report that BOTDR measurements detected movement at the seafloor consistent with ≥1 cm dextral strike-slip on the North Alfeo fault, 25 km offshore Catania, Sicily over the first few months of observation. In Oct. 2020 a dedicated 6-km long fiber-optic strain cable was connected to the cabled deep-sea infrastructure of the INFN-Laboratori Nazionali del Sud/IDMAR offshore Catania at 2060 m and deployed across this submarine fault, thus providing continuous monitoring of seafloor deformation at a spatial resolution of 2 m. The laser observations indicate significant elongation (20 - 40 microstrain) at two fault crossings, with most of the movement occurring between 19 and 21 Nov. 2020. A network of 8 seafloor geodetic stations for direct path measurements was also deployed in Oct. 2020, on both sides of the fault to provide an independent measure of relative seafloor movements. These positioning data are currently being analyzed. In Jan. 2022 during the FocusX2 marine expedition, 20 ocean bottom seismometers were deployed for 12-14 months, which together with 14 temporary land-stations as well as the existing network of permanent stations (both operatedbyINGV) will allow us to perform a regional land-sea passive seismological monitoring experiment. 9 additional OBS will be deployed in late-July 2022 increasing the total number of OBS to 29. Sub-bottom profiling and micro-bathymetric data acquired by an AUV (Autonomous Underwater Vehicle) illustrate the morpho-tectonic complexity of the strike-slip fault system and its expression at the seafloor, with numerous sub-parallel splays and narrow, N-S trending, tilted domino blocks.

FocusX temporary land-network (FXland), seismic data and preliminary analysis

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Keywords: seismic network, seismicity, deep structure, Ionian Sea.

In the frame of FocusX2 project INGV (Osservatorio Nazionale Terremoti and Osservatorio Etneo) and UniCal (Laboratorio di Sismologia) are deploying, from the end of 2021 to January 2023 a temporary seismic network for an active/passive seismological experiment to record regional and global seismicity in the Ionian Sea. The goal of this experiment is to improve the detection of seismicity in the Ionian Sea area and the accuracy of the locations; to better define the crustal structure of the region and find patterns related to fault systems. The seismicity in the area is possibly the result of two types of tectonic activity at different depths: a gently NW dipping subduction interface of the Calabrian subduction zone, and the strike-slip fault systems in the Ionian Sea, well expressed in the morpho-bathymetry and observed in previous seismic profiles.

The deployment of 13 temporary land stations, FocusX temporary land (network code 1J) https://doi.org/10.13127/SD/O5QWM6WJCD along the coasts of eastern Sicily and SW Calabria, is going to complement the permanent networks (network codes IV, MN and IY); in the same period OBS stations are deployed at sea: FocusX temporary OBS-network (network code XH).

The land stations are equipped with two different type of digitizers: Reftek 130 (12), and SaraSL06 (2); and with three different type of velocimeters: Trillium 120C (10), Le 5s (2) and ss08 60s (2).

Continuous data are transmitted in real time at the INGV Rome acquisition system, used in the seismic surveillance, archived and distributed in EIDA https://eida.ingv.it/it/.

In the deployment period 23rd December 2021 - 9th May 2022 regional seismicity (area between Lat 36.5-38.2 Lon 14.5-16.0) include 390 events located by the INGV seismic surveillance system, two of them with magnitude larger than 4.0 as well as 56 teleseismic earthquakes with magnitude larger than magnitude 6.0, two of them larger than 7.0. The two local events with M>4.0 and some of their aftershocks, were analyzed by the analysts of the Italian Seismic Bulletin including all the stations of the FXland 1J network.

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Observed deformation along a submarine cable offshore Catania between 2020-2021

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Keywords: ground deformation, fiber optics, seafloor geodesy, monitoring.

As part of the FOCUS project, a BOTDR (Brillouin Optical Time Domain Reflectometry) interrogator has been connected to the INFN-LNS (Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud) fibre optic cable that extends from the port of Catania 25km offshore to TTS (Test Site South) in a water depth of 2km. BOTDR interrogators measure the shift in the Brillouin frequency to estimate temporal changes in temperature and longitudinal strain along the cable based on a linear relationship between the change in frequency and strain/temperature. The location of the temperature/strain change is calculated by multiplying the time between transmission of the laser light to the arrival of the backscatter light at the interrogator by the velocity of the light in the fibre. In this way the BOTDR interrogator converts a standard telecommunication fibre optic cable into an array of virtual strain/temperature sensors.

The VIAVA BOTDR interrogator has been continuously recording the relative strain changes at 2m spacing along the length of the INFN-LNS cable every 2 hrs since May 2020. In the period 2020 to 2021 large ground deformation linked with severe deformation on Mt Etna were observed by terrestrial GNSS stations. This study compares the evolution of the Brillouin frequency shift observed along the INFN-LNS cable with nearby geodetic stations. However, close to the coast seasonal variations in water temperature are on the order of 5°C, consequently this effect must be removed from the signal. To do so, numerical simulations of seasonal sea temperature specific to offshore Catania have used to estimate the change in temperature along the cable during the year. The simulated temperature change is then converted to a Brillouin frequency and removed from the frequency shift recorded by the interrogator before being converted to a strain measurement. This processing produces a relative strain time series with the first order temperature effect removed. In this time series, we observe short wavelength strain changes which appear abruptly and remain constant for a number of months. This feature occurs at a distance of 6-7 km down the cable which is the point at which the cable is located at the top of a submarine canyon and are therefore possibly gravitational failures. Closer to the coast (i.e. < 5km), strain variations are more enigmatic with a rapid decrease in strain in mid-October 2020 occurring at the same time as nearby geodetic station recorded a transient event; however, a large increase in strain along the same section of cable in June 2020 shows no such correlation with on land instrumentation.

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Investigating controls on co- and post-seismic smectite production in fault cores

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Keywords: fault zone, fault gouge, earthquake, geochemistry, fault healing.

Clay rich layers in fault gouge are mechanically weak and appear to preferentially focus rupture propagation (Boulton et al., 2017; Chester Frederick et al., 2013; Holdsworth et al., 2011). Smectite, a frictionally and chemically complex clay mineral, has the characteristic of containing high proportions of mineral-bound water that gets released at ~100-150 °C on breakdown to illite (Vrolijk, 1990). Frictional heat-induced smectite dehydration may result in thermal presurization of pore fluid within low permiability fault gouge (Wibberley & Shimamoto, 2005) and is a slip-weakening mechanism, allowing large earthquakes to occur. On the other hand, high proportions of smectite can cause strain to be expressed as aseismic creep or small, regular earthquakes (Carpenter et al., 2011). Understanding the controls and timing of its formation during fault rock production is paramount to elucidating post-seismic fault strength evolution, rate of fault healing, and dynamic fault weakening mechanisms.

An excellent fieldsite to investigate smectite is the Alpine Fault (AF) in New Zealand which historically produced large earthquakes and is currently locked (Sutherland et al., 2007). Whole rock major and trace element chemistry of AF damage zone reveals pervasive hydrothermal alteration, with significant additions of carbonate and water corresponding to calcite and clay mineral growth. These fluid-mediated reactions show the greatest mass change and water addition within Principle Slip Zone (PSZ) gouges with produced clays displaying higher oxygen isotope ratios than those within the surrounding damage zone. Smectite is restricted to PSZ gouges and thus poses the question as to why that is. In this work, we reverse-engineer these mineralogically complex natural samples to simplified synthetic compositions that enables identification of exactly what minerals, fluid compositions, and physical conditions favour fault core smectite formation. To dissect processes controlling co- and post- seismic chemical reaction pathways, we study the evolution of these samples through a two-stage experimental procedure: samples undergo high velocity rotary shear in contact with hydrothermal fluid to simulate earthquake slip, followed by steady state shear akin to post-seismic conditions to replicate fault core healing processes. Fully characterising (mineralogically, chemically, and isotopically) gouges and fluids at each stage of our experimental method will enable us to identify the effect of changing specific conditions on fluid-rock interactions that control mineral formation.

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The 8 February 2022 Santa Tecla creep event on Mt. Etna: observations from field, InSAR deformation and fault detachment

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Keywords: Etna, aseismic creep, surface faulting, volcanotectonic deformation.

Fault creep along the eastern flank of Mt. Etna has been documented since the end of the 19th century (Rasà et al., 1996; Azzaro et al., 2012) and significantly contributes to the surface faulting hazard in the area.

On 8 February 2022, an episodic aseismic creep occurred along the Scalo Pennisi Fault (ITHACA Working Group, 2019) close to the Santa Tecla coastline. We observed the reopening of pre-existing ground breaks mostly as pure dilational mode I fractures. We mapped the creeping surface ruptures and collected data on displacement, length, and pattern of ground breaks. Ground ruptures affected roads, walls and buildings for a length ~350 m, mainly distributed along the southernmost part of the fault.

Differential InSAR data, acquired in both descending and ascending views (Descending 29 Jan-10 Feb 2022; Ascending 4-20 Feb 2022), allowed us to decompose Line of Sight (LOS) displacement into horizontal and vertical components of deformation. We detect ~700 long and ~400 m wide deformation zone with a downward and eastward motion (max values 1,5 cm) consistent with a listric normal fault.

Preliminary calculations using a simple area balancing approach to estimate the depth of detachment of the fault (Groshong, 1994), indicate a possible low angle detachment at very shallow depth ~150 m.

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The scaling relations of faults and earthquakes: a multi-scale approach for orogen internal seismic deformation

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Keywords: Orogen internal seismicity, multi-scale mapping, power law.

Understanding orogen internal seismicity in regions of collisional tectonics with limited recent crustal deformation such as the Central Alps is a major challenge, mainly due to the diffuse spatial patterns of the seismic activity and the surface-exposed faulting. To obtain a more profound understanding of the seismic deformation processes in such regions, quantitative information about (i) the pre-existing fault patterns, (ii) the seismic activity and (iii) their relation is required. Direct linking of subsurface earthquake activity with individual surface-exposed fault structures is however often ambiguous. Additionally, pre-existing fault patterns at seismogenic depths cannot be resolved at sufficient resolution, which means that one is restricted to the use of surface observations to characterize the pre- existing fault patterns. Nevertheless, both earthquake magnitudes (Gutenberg-Richter law) and geometric fault properties (e.g. length, displacement) have been proposed to follow power-law distributions, enabling to statistically compare fault and earthquake patterns. Power laws are interesting because they can have important implications for the physical properties of a system. Particularly noteworthy here is a system's scale invariance, which denotes the absence of a characteristic length scale. This means that information obtained from outcrop-scale observations can be directly translated to larger scales. Identification of power laws could thus validate such scale transformations and give indications about the proportion of pre-existing faults that cause seismic activity. Because of several sampling biases, e.g. due to poor outcrop conditions or limited image resolutions, it is however challenging to accurately extract the geometric properties of surface-exposed faults.

In this work, we aim to obtain quantitative information of the pre-existing patterns of surface-exposed faults for different tectonic units in the Central Alps. We therefore map fault traces on aircraft- and drone-based orthophotos and digital elevation models for different localities and evaluate their length distributions, with a special emphasis on identifying power laws. Since single-scale fault maps only yield a limited range of fault lengths and thus make the identification of power-law distributions challenging, we integrate fault maps from different mapping scales. This multi-scale approach not only increases the reliability of the power laws but extends the valid length ranges and adds robustness to the identification of possible sampling bias effects. We then compare the obtained power-law distributions of the different localities to quantitatively describe the pre-existing fault patterns of the respective tectonic units.

In a next step, we assess how the obtained power-law distributions of surface-exposed faults of the different tectonic units relate to Gutenberg-Richter scaling law of the regional earthquake catalog. Together with the well-known fact that earthquake magnitudes scale with fault lengths, such statistical comparison of the scaling relations of faults and earthquakes could yield interesting insights into orogen internal seismic deformation and fault reactivation processes.

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Re-evaluation of the historical surface rupture of 1912 Acambay earthquake, Central Mexico. Morphological, paleoseismological and historical data

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Keywords: active tectonics, Trans-Mexican Volcanic Belt (TMVB), 1912 Acambay earthquake, surface rupture.

The November 19th, 1912, Mw 7 Acambay earthquake is the most documented historical crustal earthquake associated with surface rupture within the Trans-Mexican Volcanic Belt. Although the event has been widely studied, inaccuracies and contradictions in historical documents have led to different interpretations of the surface ruptures and other superficial deformations by the scientific community. Therefore, a re-evaluation of the primary and secondary effects of the earthquake is necessary to better understand the fault rupture, there consequences for future rupturing events in the area and, with it, the accurate evaluation of the seismic hazard for the Mexico most populated region.

In order to better characterize the 1912 rupture in the Acambay graben, an multidisciplinary approach was adopted, integrating A) early instrumental seismological data, B) historical description of geological and structural coseismic effects, which led to reinterpret the intensity distribution within the graben using earthquake environmental effects evaluated with environmental seismic intensity scale (ESI-07), and C) new paleoseismological data allowing a better characterization of the surface ruptures along the central fault of the graben.

The detailed analysis of primary and secondary effects from a paleoseismological, geomorphological and cartographic approach allow to obtain a new and more precise mapping of the 1912 rupture with a better evaluation of associated displacements and an interpretation of secondary effects reported in the different part of the graben. Our results indicate that the rupture not only occurred along the northern border of the graben but also on the southern border and along the central fault system, confirming that multifault rupture event scenarios, with related higher magnitudes, have to be considered in this region of Mexico that concentrates more than 50% of the population of the country.

S3.

Numerical & analogue modeling of geological processes

CONVENERS & CHAIRPERSONS

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Counterintuitive fracturing in a multilayer under extension: natural examples and numerical modelling

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Keywords: fracture network, numerical modelling, layered sequence.

Improving our understanding of fracturing processes thanks to observations on outcrop analogues and mechanical modelling can help modelling fracture networks in reservoirs of geofluids. Here we investigate a counterintuitive behavior in mechanically layered sequences of different rocks where we observed a more intense fracturing, both in terms of fracture density/intensity and number of fracture sets, in more competent layers.

In the Island of Gozo (Malta) we have characterized normal fault zones in porous carbonates, and we found that, in the relatively softer units, the thickness of damage zones is about 1/30, and fracture intensity is about 1/10 (at the same distance to the fault core). In metamorphic rocks in the Alps - gneiss, prasinites and calcschist showing different composition and contrasting mechanical properties, we have observed a strikingly similar situation in domains fractured under horizontal extension far from major faults, with an inverse correlation between mechanical parameters and fracturing parameters.

Simulations with a geomechanical finite element code show that, during horizontal extension of a multilayer with variable elastic properties, deviatoric stresses build up much more quickly in stiffer rocks. This is because all the different layers are subject to the same strain (horizontal stretching), and stress is controlled by the elastic moduli, resulting in higher deviatoric stresses in more rigid layers. At some point, brittle failure (simulated as plastic yield in continuous FEM codes) takes place in the stiff layers, well in advance with respect to failure in the soft ones. At this point, the simulation reveals a situation where fracturing is confined in the stiff layers. As horizontal stretching continues, failure can occur also in the soft layers, but always in a more limited way.

This mechanical behavior, observed in very different tectonic environments and lithological units, can be of general relevance and might result in a reevaluation of paradigms used to predict fracturing and hydraulic properties of mechanically layered reservoirs.

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Analogue models of progressive arcs: characterization of finite strain in a ductile layer

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Keywords: Analogue models, progressive arcs, strain, ductile layer, fold-and-thrust.

Arcuate external fold-and-thrust belts of orogenic systems that acquired their curvature progressively and simultaneously with thrusting, that is, progressive arcs, have been modeled by Jiménez Bonilla et al. (2020) with an innovative design of the experimentation table. They made use of a deformable backstop that push from behind the initial parallelepiped while the amplitude of the arc indenting in the analogue model increased. They were able to model arcuate, ductile-brittle fold-and-thrust wedges with a two-layer pack (viscous silicone below brittle sand).

To further investigate strain and its partitioning in the ductile layer, we used the same experimentation table but with a pack formed only by silicone. A grid drawn on top of it permits us to visualize the 2D horizontal strain. As a whole the ductile layer deformed heterogeneously and in the most internal part of the model, the initial grid progressively adapted to the arcuate backstop geometry. As expected, no heterogeneities associated with the nucleation of discrete structures have been observed.

We inscribed best fitting ellipses in several grid cells. Assuming silicone deforms isochorically, a vertical strain axis is deduced from the two horizontal ones, thus producing strain ellipsoids. This permits us to evaluate not only displacement vectors or grid vertical-axis rotations but also other 3D deformation parameters depending on their position with respect to the backstop. Finite strain is oblate and increases towards the backstop and slightly towards the apex. Ellipsoids rotate towards parallelism with their respective backstop nearest segment. This rotation is larger close to the backstop.

These data all together suggest that the deformation transmitted to the ductile layer is essentially an orthogonal flattening and that most of the rotational component of the deformation is absorbed at the backstop-silicone interface and in the lateral parts of the arc. Our experiments shed light on the deformation associated with the limbs of progressive arcs in natural cases in which an increase of the backarc area is observed. Next step will be to compare them with the ductile-brittle experiments of Jiménez Bonilla et al. (2021) and to complete all these experiments to understand the influence of the thickness of a brittle sand layer over a ductile one composed of silicone (work in progress).

Acknowledgements: This work was supported by projects EST1/00231, PGC2018-100914-B-I00, and UPO 1259543.

Jiménez-Bonilla A., Crespo-Blanc A., Balanyá J.C. & Díaz-Azpiroz M. (2020) - Analog Models of Fold-and-Thrust wedges in Progressive Arcs: A Comparison with the Gibraltar Arc External Wedge. Frontiers in Earth Science, 8(72). https://doi.org/10.3389/feart.2020.00072.

The immense range of deformation structures evolving in highly anisotropic materials

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Keywords: anisotropy, fabric, crenulations, shear bands, folding.

Rocks often have planar fabric elements or foliations. A foliation can be due to bedding in sedimentary rocks, compositional layering in igneous rocks or by the formation of cleavage or schistosity in metamorphic rocks. An intrinsic mechanical anisotropy arises due to the alignment of anisotropic minerals while they develop a crystallographic preferred orientation (CPO). Deformation of anisotropic rocks can lead to the development of various structures such as folding and associated crenulations, as well as shear zones and shear bands. It is thus essential to systematically understand how anisotropy variations control the rock deformation.

We use the Viscoplastic Full-Field Transform (VPFFT; Lebensohn & Rollett, 2020) crystal plasticity code coupled with the modelling platform ELLE (www.elle.ws) to simulate the deformation of an intrinsically anisotropic material in dextral simple shear starting with (1) a random CPO and with (2) a single maximum CPO, which we vary from being parallel to perpendicular to the shear plane. We also vary the degree of anisotropy. We use passive material markers to visualize the finite strain field and vary their orientations similar to the variation of the CPO. We use a generic mineral with hexagonal symmetry and preferred slip along the basal plane.

A highly anisotropic material with a random c-axis orientation develops small-scale anastomosing shear bands when layering is parallel to the shear plane. However, the material experiences thickening and thinning during rotation with the development of small-scale folds, or stretching, depending on the orientation of the tilted layers. When layers get stretched, they mix relatively fast. Three kinds of deformation behavior develop when deforming a highly anisotropic material that already has a CPO: (i) Distributed localization with anastomosing shear bands, (ii) synthetic shear zones oriented parallel to the shear plane, and (iii) antithetic and rotating shear bands. Transitional regimes can also develop. The finite strain field shows completely different structures depending on the orientation of the passive layers. Folds develop in microlithons which do not develop when the passive layering is initially horizontal. Very different types of fold patterns arise depending on the orientation of passive layers, while deformation structures get overprinted or preserved after very different amounts of strain. The amount of strain at which distinct structures develop, and how they evolve with progressive deformation, are also systematically evaluated. Only very high anisotropies lead to distinct deformation structures. Frequency distributions of von Mises strain rates show that the presence of high anisotropy triggers power-law distributed strain rates.

The results show the range of deformation structures that can develop in anisotropic materials, and highlight the limitations of using crenulations and other related structures to reconstruct the structural evolution of deformed rocks, as structures can be very misleading.

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How do lithospheric thickness and strength variations facilitate the breakup of ancient cratonic lithosphere?

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Keywords: numerical modelling, rifting, craton, North China, inheritance.

Many continental rifts form adjacent to ancient cratons and exploit mobile orogenic belts to localise deformation. The North China Craton formed by the collision of two Archean blocks in the Paleoproterozoic that formed the broad collision zone known as the Trans North China Orogen. Due to the unique evolution and recent geological destruction of the North China Craton, the craton shows two different modes of extension that are separated by space and time. The Eastern Part exhibits wide, distributed rifting with abundant magmatism in the Paleogene while the Western Part shows a series of narrow rifts that formed during the Neogene in the vicinity of Proterozoic orogens. However, the exact mechanism that led to the development of these vastly different rift systems remains debated. Here we use the geodynamical tool ASEPCT to perform 2D thermos-mechanical modelling to explain the role of variable lithospheric strength and inherited lithospheric weaknesses in the development of these two rift systems. We found that a wide distributed rift will develop in thick crust over non-cratonic lithosphere, while the adjacent cold thick cratonic lithosphere will accommodate almost no strain. A period of quiescence between the two rift episodes is important to strengthen the thinned eastern block and facilitate the rift migration to the west. Only with an inherited lithosphere scale weak zone does a narrow rift form. Our results show how lithospheric thickness and strength variations as well as associated discrete zones of lithospheric weaknesses can influence the style of rifting and facilitate the breakup of an ancient craton. These results are widely applicable to many other continental rifts in the world that often form around cratons such as the Baikal rift or the East African Rift that show similar behaviours. It may also question the need for two different tectonic regimes to explain the differences between the circum-Ordos rifts and the wide rifts in the North China plain.

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Full-field numerical simulation of dynamic recrystallisation in polycrystalline halite

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Keywords: grain boundary migration, dynamic recrystallization, halite microstructure, strain localization.

The viscous flow of salt rocks leads to the development of tectonic structures such as detachments and salt diapirs. Moreover, evaporites are key in petroleum systems and are potential storage rocks for products such as hydrogen, natural gas or radioactive waste due to their low permeability and high ductility. Therefore, understanding the mechanical behaviour of evaporites are of key scientific and economic significance. Numerical modelling has become a useful method to study rock deformation processes at multiple scales. However, modelling the microstructural evolution of rock salt grain aggregates is challenging due to the anisotropy and complex plastic behaviour of halite at the single crystal level, together with the interplay between crystal-plastic deformation and dynamic recrystallisation processes.

In this contribution we present, for the first time, results of full-field numerical simulation of dynamic recrystallisation (*DRX*) of halite polycrystalline aggregates during simple shear deformation. The models are based on the approach that couples a viscoplastic deformation code that simulates dislocation glide (VPFFT) and the numerical software platform ELLE (Bons et al., 2008; Gomez-Rivas et al., 2017) that explicitly simulates intracrystalline recovery, nucleation and grain boundary migration. The simulations show that the numerical approach can reproduce the evolution of dry halite microstructures from laboratory torsion deformation experiments at 100-300°C up to high shear strains of 3 and provides new insights into the dynamic evolution of polycrystalline halite during dynamic recrystallisation. Our simulations show how subgrain rotation recrystallization (SGR) and grain boundary migration (GBM) strongly influence the microstructure (grain size and grain shape) at different temperatures and strain rates, while the development of crystallographic preferred orientation (CPO) seems to be affected less. Grain boundary migration enhances the activation of the {100} system, which leads to strain-hardening, but intracrystalline recovery processes reduces this effect. Inferring the finite strain history from the microstructure is challenging, as strain-localisation bands can be masked by high-temperature (or low strain rate) induced GBM.

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Gomez-Rivas E., Griera A., Llorens M.-G., Bons P.D., Lebensohn R. & Piazolo S. (2017) - Subgrain rotation recrystallization during shearing: insights from full-field numerical simulations of halite polycrystals. Journal of Geophysical Research: Solid Earth, 122(11), 8810-8827.

Shear localization: analog modeling and anisotropy of magnetic susceptibility

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Keywords: simple shear, AMS, deformation, microstructure, localization.

There is a broad discussion related to origin of the magnetic fabric, its relationship with the bulk deformation and strain memory of rock. The analogue modelling of magnetic fabric in shear-zones was used to explore the time and space relationships between the finite strain and the anisotropy of magnetic susceptibility (AMS) by providing new experimental data. The AMS as a dimensionless material parameter describes the degree of magnetization of a material in response to an applied magnetic field in different directions. AMS measurements reflect a combined magnetic signal of shape preferred and crystallographic orientation of all rock forming mineral grains. Therefore the AMS has become a broadly used technique in geology as useful and quick method to quantify the internal rock fabric. However, the lack of comprehensive knowledge base about the governing processes of AMS in rocks can make the AMS interpretation difficult.

Previously, a relationship of AMS with increasing strain has been studied experimentally in plasticine, deformed sandstones, magnetite bearing sand bonded with cement and during preparation and compaction of calcite and muscovite aggregate and simple shear experiments on mixture of silicone and wax. A large shear-box was designed to enable different strain rates and also shear-zone of variable width. The experiments were produced with the coloured plaster of Paris with homogeneously admixed fine-grained magnetite and powder retarding the solidification reaction. The used analogue material displays a peculiar strain-rate dependent rheology (thixotropy) and is capable to well-reproduce the strain localization up to brittle failure and very well corresponds to natural rocks. Experimentally produced magnetic fabric related to simple shear deformation in plaster is analysed in terms of the AMS.

By varying experimental strain rate we were able to model not only ductile to brittle behaviour of the shear-zones, but also observe the AMS evolution with the strain localization. Correlation is observed between the strain rate and the width of the shear-zone identified from the reoriented magnetic fabric. Very interesting is development of the AMS shape parameter T from the edge of the shear-zone to its core. AMS ellipsoid changes from background primary fabric to more prolate shapes in shear-zone margins and then back to neutral shapes in core of shear-zone. This gradual development is probably connected with the evolution of the constriction fabric and/or transposition and the subsequent destruction of the primary magnetic fabric in the middle of the shear-zone. Our experiments suggest that AMS-strain relationship is not straightforward and proper interpretation of AMS fabric from shear-zones requires additional analyses to by correctly interpreted.

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For how long can crystallographic preferred orientations be preserved under flow transitions?

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Keywords: ice microstructures, crystallographic preferred orientation, ice-sheet flow, flow transitions.

Deformation of polycrystalline anisotropic rocks by dislocation creep leads to a crystallographic preferred orientation (CPO). The CPO evolves according to the flow kinematics, and importantly depends on the ease of glide on the different slips systems. However, linking the development of CPOs to the flow history requires a proper understanding of the rock aggregate's microstructural response to flow transitions. An ice crystal is strongly anisotropic because it deforms predominantly by the glide of dislocations on the basal plane (0001) (Duval et al., 1983). In this contribution we investigate the influence of ice deformation history on the CPO development by means of full-field numerical simulations at the microscale VPFFT (Lebensohn & Rollet, 2020) inside the software platform ELLE (https://www.elle.ws; Bons et al., 2008; Llorens et al., 2017). A volume of ice is deformed under combinations of two consecutive events, in order to observe how the deformation regime switch impacts the CPO. The results indicate that the second flow can change entirely an inherited CPO within a natural strain lower than 1.2, with a range of transitional fabrics. However, when the elongation axis of the finite-strain ellipsoid from the first and second regime are in the same plane, the inherited CPO is slowly modified. Therefore, observed CPOs are reliable indicators of the current flow conditions, as they usually adapt to them in a relatively short time. However, interpretations of past deformation events must be carried out with caution, particularly, in areas with complex (multi-stage) deformation histories.

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Mechanical characterisation of a new Sand-Hemihydrate rock-analogue material: Implications for modelling of brittle crust processes

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Keywords: analogue modelling, granular materials, dynamic scaling, fault damage zone.

In dynamically scaled experiments the analogue materials play a critical role, defining the processes that can be simulated and the structures observable in the model. The dynamic scaling enables the direct comparison between model and natural system (Hubbert, 1937). To obtain such a model, the properties of model material and rock prototype, including cohesive strength, density and frictional parameters, must be scaled. A large variety of materials has been applied in analogue modelling studies to address the physical and mechanical requirements for the simulation of (i) upper crust, (ii) middle crust and (iii) lower crust and mantle processes (Reber et al., 2020, and references therein).

We investigated the mechanical and physical properties of a new Granular Rock-Analogue Material (GRAM) introduced in Massaro et al. (2021), analysing how its applications in dynamically scaled experiments can enhance the comprehension of the fault and fracture processes occurring at the scale of the damage zone. GRAM is an ultra-weak sandstone composed of quartz sand, hemihydrate powder and water, capable to deform by tensile and shear failure under variable stress conditions. GRAM aggregates were tested in different mixing ratios, from 1% to 4% in weight of hemihydrate powder. The mechanical test series involved GRAM aggregates and their component materials (quartz sand and hemihydrate powder), analysing their fundamental properties, including uniaxial compressive strength and elastic modulus from uniaxial compression tests and shear strength, cohesion and internal friction coefficients from ring-shear tests. Successively, the dynamic scaling was calculated, showing that GRAM aggregates can provide a model resolution of higher detail with respect to quartz sand, mainly due to their higher cohesion values (3-15 kPa). In detail, considering a rock prototype with 15 MPa of cohesion and 2.43 g cm^{-3} of density, GRAM at 2% enables a length equivalence of 1 cm in the model corresponding to 10.65 m in nature. Furthermore, the model resolution can be adjusted by modifying the mixing ratio of quartz sand and hemihydrate. Therefore, the application of the new GRAM aggregates in physical experiments can allow the investigation of geological processes at the outcrop scale, enabling the development of physical models at a new scale of resolution.

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The effect of the volume fraction of garnet on strain localization mechanisms in eclogite: Insights from high temperature – high pressure deformation experiments and numerical simulations

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Keywords: eclogite deformation, microfabric, high temperature-high pressure experiments, numerical simulations.

We performed deformation experiments and numerical simulations on omphacite-garnet aggregates to gain insight into the deformation behaviour of dry eclogite with special focus on the role of garnet fractions between 25% and 100% for strain weakening. The triaxial deformation experiments and numerical simulations were performed at a temperature of 1000°C, a confining pressure of 2.5 GPa, and a strain rate of 3×10^{-6} s^{-1}. The combination of the results from the numerical simulations with experimentally derived microstructures enables us to determine the spatial and temporal evolution of strain and strain rate and identify microstructures characteristic for strain localization.

In accord with phase-mixing models, our experimental and numerical results show that eclogite strength increases with increasing garnet content following a log-linear relation. Contrary to common phase- mixing models our experiments indicate mechanical weakening after a short period of steady state creep. The intensity of strain weakening increases with increasing garnet content. Microstructural investigations and numerical simulations suggest that weakening results from increased strain rates in localized conjugated micro-shear zones. These zones are characterized by fine-grained omphacite and garnet; however, the grain size reducing mechanism varies. In aggregates up to a 50% garnet, internally strained omphacite clasts, bulges and low angle grain boundaries indicate that grain size reduction takes predominately place by recrystallization mechanisms. The fracture-dominated fabric in eclogite with

≥75% garnet indicates grain size reduction via cataclasis. Microstructural investigations are supported by numerical simulations which show that deformation is the more accommodated by brittle mechanisms in eclogites the higher their garnet content.

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Modeling the influence of a non-planar bedrock topography on flow dynamics and steady state geometry of ice sheets

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Keywords: ice sheet, folding.

Airborne radargrams of Greenland's ice sheet clearly show internal stratification, which was (sub-)horizontal during its deposition. In some regions, these layers mark internal large-scale folds with amplitudes of 500 m and more within the ice, which mark the internal deformation of the ice sheet. Folds occur in the spatial context of ice streams as well as in slow-moving ice. These folds can be used as a very useful tool to understand the flow behavior of ice sheets. In oder to better our understanding of the internal deformation processes of the Greenland ice sheet, we create numerical models from the perspective of the structural geologist. Just like many other deformation structures known to geologists, the formation of folds must be thought of as a combination of initiation or localization of a proto-fold and its subsequent growth.

Here we investigate the presence of a 'bumpy' bedrock topography on the internal deformation of ice using the Particle-in-Cell geodynamics code 'Underworld2' (Mansour et al., 2020), which allows us to model the pathways of internal deformation markers and of the free surface.

Geothermal heat flux creates a vertical temperature gradient within ice sheets. The temperature increase from top to bottom finds its rheological expression in a decrease of density and effective viscosity, effectively forming a low viscosity, low density (LVLD) layer at the basis. Folding concentrates LVLD material in the fold core, while the surrounding basal layer is depleted of it. This impacts the flow dynamics and the further internal deformation of the ice sheet.

The bedrock topography has an important impact on the geometry of the basal LVLD layer and thus a) on the layer geometry in steady state and thereby b) on the local flow dynamics and internal ice sheet deformation. Here we present experiments of the internal geometry of flowing and resting ice on a non-planar bedrock topography. The experiments aim to be reference simulations in order to understand the internal deformation, the flow dynamics and to identify relevant boundary conditions.

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Kinematics of direct faulting in the Bradanic Foredeep (Southern Italy) retrieved trough geomatic tools and faulting activity investigated by space-borne multi-temporal SAR interferometry

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Keywords: Bradanic Foredeep, carbonate basement, tectonic, SAR interferometry.

The Bradanic Foredeep (Southern Italy) is a tectonic trough filled from late Pliocene with a huge regressive soil sedimentation. Starting from Pleistocene age, the entire region underwent a distensive tectonics towards West whose effects can be seen through the morphologies of both the Mesozoic carbonate basement and of the above more recent fillings. Particularly, NW – SE lineations border flat surfaces at the edge of big soil masses, tilted along direct faults. The loss of continuity of the prevailing clay masses produces other significant processes concerning underground fluids flow and several mud volcanoes. The process has been verified and confirmed also from some deep underground works (long tunnels in the region). Availability of geomatic tools, like high resolution DEMs of the ground surface and the top of the Mesozoic basement allows us to retrieve through simple rules the kinematics of the faulting of the quaternary filling, i.e. the horizontal and vertical displacement around the fault tracks and the rotation of the old flat terraced surfaces. Fault shear surfaces develop tracks parallel to the direction of the buried basement, and this is a relevant correlation to analyze to evaluate causes and type of the local tectonics.

This study should be relevant for a new reading of the regional geodynamic, since previously those landforms were interpreted as an effect of local erosional processes, without links to the shape and the tectonic of the basement. The 3D-representation of the detached masses helps to identify the true causes of the direct faulting, which could be not always linked to tectonics, not currently active in these regions. The feasibility of using space-borne multi-temporal SAR interferometry to support this displacement analysis has been investigated. The interest of this methodology is in the extended time and space span of the existing data, covering over 15 years, and the capability of detect sub-millimetric displacements.

The effect of dynamic recrystallisation on olivine microstructures: a numerical study

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Keywords: Olivine, plastic deformation, simple shear, dynamic recrystallisation, numerical simulation.

The dominant rocks in the upper part of the Earth's mantle are peridotites, mainly composed by olivine. Crystal preferred orientation (CPO) in olivine is produced through viscoplastic deformation during mantle flow, where the CPO of a-axes in olivine polycrystalline aggregates is aligned to the flow direction. As a result, olivine's rheological qualities will have an impact on a variety of geological processes. The rheological behavior of olivine is highly connected to the crystal preferred orientation (CPO) (Hansen et al., 2012) and grain size, according to experimental research (Karato et al., 1986).

Therefore, to explore the crystal preferred orientation (CPO) and grain size development of olivine under viscoplastic deformation including dynamic recrystallization (DRX), we performed microdynamic numerical simulations of olivine aggregates varying the initial grain size. We analise how dynamic recrystallization (DRX) impacts on the microstructure and rheology of olivine under simple shear boundary conditions. We use the viscoplastic full-field formulation (VPFFT) approach, which is based on the Fast Fourier Transform, in conjunction with the ELLE modeling platform (https://www.elle.ws; Bons et al., 2008; Llorens et al., 2020; Piazolo et al., 2019) to simulate the dynamic recrystallization processes in order to obtain the microstructural and CPO evolution of the olivine polycrystalline aggregate.

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Ice modeling indicates formation mechanisms of large-scale folding in Greenland's ice sheet

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Keywords: modeling, folding, formation, ice dynamics.

Radargrams reveal internal layering and large-scale folding (up to >500 m) in some regions in Greenland's ice sheet, both within ice streams such as the North-East Greenland Ice Stream (NEGIS) and away from it in the slow-moving ice. These folds are significant to understand the flow behavior of ice sheets and to predict future developments. However, there is no consensus yet on how these folds form. There is still a need for better numerical modeling of the formation of large-scale folds, especially concerning vertical temperature, viscosity and density gradients and rheological anisotropy of ice, and therefore to get insights into the actual formation mechanisms.

We use the 3D Finite Element Method with the geodynamic code Underworld2 to simulate ice movements mainly under the following conditions: lateral convergence, vertical viscosity and density gradients from temperature contrast, viscoplastic anisotropy due to crystallographic preferred orientation (CPO), and bedrock topography. Vertical Temperature gradient for ice layers is -30 °C at the 60% top volume (cold ice) and gradually increases to -5 °C at the base (warm ice) with a parabolic equation, while ice density follows the trend as in equations for density/temperature. The power-law viscosity is accordingly derived from temperature and also the strain rate related to lateral convergence. Transverse isotropy is assumed and calculated from the CPO. Variations in bedrock elevation are also set in some simulations.

In the results, folds usually start from the interface of the warm and cold ice and spread into cold ice layers. Their amplitudes tend to decrease upwards towards the surface, as is observed in ice sheets. Folds can form at places without bedrock bumps but are amplified most around big bumps. The results explain that folding is controlled by: 1) soft (warm) basal layers which dominate on the large scale, 2) anisotropy due to the CPO that can also produce small-scale crenulations, 3) bedrock topography becoming initial seeds for big folds, 4) buoyant (warm) ice cores may amplify anticlines after their initial formation. Our modeling highlights the special physical properties of ice and could bring new views to the ice community on the dynamics of ice flow.

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S4.

Tectonics, Structural Geology and geophysical exploration

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Characterization of fracture patterns in Lower Cretaceous Platform carbonates: examples from the Iberian Chain

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Keywords: fracture networks, Maestrat basin, carbonates, photogrammetry, reservoirs.

The estimation of porosity and permeability in subsurface limestone successions is essential for reservoir characterization, both in terms of hydrocarbon production and also for Geo-Energy applications. Most carbonate reservoirs are highly fractured, and thus permeability is typically controlled by fracture networks. The characterization of subsurface reservoirs is mainly based on seismic reflection and the study of well-logs and drill core. However, the resolution of seismic datasets is relatively low, and cannot provide information on subseismic-scale structures. Moreover, well data and drill core analyses are limited and only show a tiny fraction of the system. Fracture lengths are normally orders of magnitude longer than the drill core diameter, making the prediction of fracture network properties extremely challenging. To overcome these limitations, outcrop analogues are nowadays widely used to understand the characteristics of subsurface fracture networks and their evolution in time. This contribution presents a study of the orientation, intensity and spatial distribution of fracture networks in an outcropping Barremian-Aptian carbonate succession of the western Maestrat Basin (Galve sub-basin) in the eastern Iberian Chain. The fracture analysis was carried out on four very distinct lithostratigraphic units, which are from oldest to youngest: Xert. Forcall, Villarroya de los Pinares and Benassal formations. The Xert and Forcall formations correspond to marls and limestones with wackestone to packstone textures rich in orbitolinids. These formations were deposited in a relatively deep marine platform and basinal settings. Above, the Villarroya de los Pinares and Benassal formations are constituted by floatstones and rudstones with rudists and corals, and thus correspond to platform top carbonates. The Lower Cretaceous succession was studied through a combination of methods, including analysis of fractures in the field, rock sampling and the quantification of fracture patterns from orthophotos and virtual outcrop models acquired with an unmanned aerial vehicle. This technique has allowed the generation of photogrammetric models for the collection of a large number of fracture datasets. Fracture patterns were carried out with FracPaq software. The first results reveal that fractures affecting the succession are mainly arranged into orthogonal systems, with dominant N-S to NW-SE and NE-SW orientations, respectively. Preliminary findings link the genesis of the regular fracture network of the two main fracture sets to the Early Cretaceous extension period affecting the eastern Iberian Plate owing to the opening of the Bay of Biscay domain. All of this information can be used to better characterize and predict fracture permeability, as well as the mechanical behavior of carbonate units from coeval subsurface hydrocarbon reservoirs, such as those from the Middle East (i.e., Kharaib Member and Shu'aiba Formation).

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TWiST, CAST, and Drill: Three projects investigating geological hazards in the Northern Caribbean

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Keywords: Caribbean, plate boundary, seismotectonics, strike-slip faults.

The transpressive Northern Caribbean plate boundary contains an active twin strike-slip fault system - the Septentrional-Oriente fault zone (SOFZ) and the Enriquillo–Plantain Garden fault zone (EPGFZ). The EPGFZ has recently generated two devastating earthquakes - the 2010 Mw7.0 Léogâne and 2021 Mw7.2 Nippes events, one of which generated a tsunami. The 2010 and 2021 earthquakes ruptured only short segments of the roughly 1,000-km long active fault system with partial reverse slip. These events are intriguing because the EPGFZ is assumed to be purely vertical / strike-slip, but their partial reverse slip testifies to the significant hazard they pose to a densely populated zone nearby. This severe risk level, in one of the least developed countries, warrants further investigation of the complex seismotectonics in this region. As such, we have developed 3 projects to characterize the geological hazards posed to Western Hispaniola. These projects include an oceanographic campaign (Haiti-TWiST), multiple onshore/offshore geophysical surveys (CAST), and an amphibious deep drilling project (Haiti-Drill). Haiti-Drill aims to understand the nature of young fault zones and the evolution of transpressional plate boundaries via deep drilling. Drilling targets and objectives were defined in 2019 at an IODP/ICDP workshop, creating a research focal point for Haiti-Drill's development. Following the workshop, we designed and proposed the Haiti-TWiST campaign and CAST project. During the Haiti-TWiST oceanographic campaign, due to be schedule in 2022 or 2023, we will investigate deep fault structures and seismic activity, as well as sample heat flow and the water column and core sediments along the SOFZ and EPGFZ submarine segments. With CAST, we aim to conduct land and sea-based surveys along the SOFZ and EPGFZ. Surveys include geological, geophysical, and paleoseismological fieldwork along the terrestrial parts of the EPGFZ and geomorphological fieldwork on coral reef terraces along Haiti's coast, spanning both the SOFZ and EPGFZ, all complemented by the Haiti-TWiST campaign. The objectives of CAST are to 1) define how the faults release stress, 2) characterize their fault structures, and 3) determine the origin of the two-fault system. Haiti-TWiST and CAST will collect data near our deep drilling targets and, as such, represent site-survey data necessary for the development of the deep drilling project, Haiti-Drill. Here, we present these 3 projects to generate interest in the work onshore and offshore Haiti and to promote international collaboration in the future deep drilling project, Haiti-Drill.

Mesoscopic structural elements in Jordan and their possible mechanisms of formation

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Keywords: deformation structures, pinch-swells structure, seismites, distorted fossils, ball-pillow structure.

Ductile and brittle meso- deformational structures are quite common in Jordan's rock formations. A detailed interpretation of such structures provides valuable information about their possible mechanism of formation and their tectonic style which is mostly related to the dominant tectonic regime that has influenced the entire region. These structures are represented by soft plastic deformation, including pinch-swells, ball-pillow segments, seismites, distorted fossils, density inversion, and chaotic breccia travertine. They are interpreted to have formed in wet unconsolidated and consolidated conditions as results of extensional, compression, and shear stresses in addition to shockwaves and over-pressurized water systems all affecting competent and incompetent rock formations.

In this article, a number of these structures are described in order to explain the nature of forces leading to their formation. The historic geological context of their formation time is elaborated and their relationship to the major structural elements and forces, such as the onset of the Syrian Arc fold belt and the Dead Sea Transform Fault or shockwaves of earthquakes or meteorite impacts are also discussed.

The results indicate that the formation of many of these mesoscopic structures can be correlated with the formation of the mega structures but the others structures have resulted from earthquakes, meteoritic impacts, and inter-sedimentary forces, such as density inversions and over-pressurized groundwater systems.

Fold and strain analysis of the large North-East Greenland Ice Stream

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Keywords: folds, mechanical anisotropy, strain analysis, ice streams.

The >500 km long and tens of kilometres wide North-East Greenland Ice Stream (NEGIS) is the largest ice stream in the Greenland Ice Sheet (GrIS). Satellite data show that flow inside the ice stream is significantly faster than adjacent to it and that NEGIS is bound by shear boundaries that are a few kilometres wide. The ice stream drains a large area of the GrIS. As the genesis of NEGIS is unclear, it remains uncertain how it may react to global climate change.

Based on a dense grid of airborne radar surveys (radargrams) we could reveal the 3-dimensional internal geometry of the internal stratigraphy. This shows that NEGIS was first a wide zone with convergent flow that resulted in folds on the 10 km scale and with convergent fold hinges. In a second stage these folds were passively sheared and displaced in the margins of the present-day NEGIS. Classical strain analysis shows that at the level of the EGRIP deep ice-drilling site in upstream NEGIS the displacement by the shear margins is ca 75 km at a finite shear strain in the order of 15-20.

With a novel method for dating folding events in ice stratigraphy, we show that NEGIS as we know it now is surprisingly young, as the shear margins in the survey area were only fully developed by ca. 2 ka BP. We propose that the localisation of shearing leading to plug flow with sharp shear margins is due to the strong anisotropy of the ice and the rotation of the lattice-preferred orientation during shearing.

Our results contradict the common assumption that NEGIS in its current form has been stable throughout the Holocene, and show that NEGIS-type ice streams can appear suddenly and have a large impact on ice sheet discharge and geometry on relatively short time scales. This is a major concern for realistic sea level projections, as global warming changes the boundary conditions of our ice sheets, which may trigger the sudden appearance of new ice streams in the future in Greenland as well as in Antarctica.

Natural fractures controlled by strike-slip faults in ultra-deep carbonates: A case study of the Middle-Low Ordovician in the Tarim Basin, China

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Keywords: ultra-deep reservoirs, strike-slip fault-controlled fractures, Tarim Basin, characterization of fractures.

Ultra-deep fractured carbonate reservoirs are important petroleum exploration targets in China. This paper studies the development characteristics of natural fractures controlled by strike-slip faults, taking the middle and lower Ordovician fractured reservoir in the Shuntuoguole as an example, combined with the published sandbox simulation results. By using three-dimensional seismic interpretation, core, imaging logging data, and sandbox simulations, the density and dip angle of structural fractures controlled by strike-slip faults are quantitatively analyzed. The faults and natural fractures in the study area can be divided into three scales: (i) large-scale fractures (small faults) in seismic data, (ii) medium and small-scale fractures in core and imaging logging data, and (iii) microfractures observed in thin sections. The fractures controlled by the strike-slip faults can be divided into two groups: high-angle and medium-low angle fractures. The density of small and medium-sized fractures controlled by the strike-slip fault zone gradually decreases with distance away from the main fault plane. Quantitative analyses of sandbox experiments and seismic attribute slices show that the width of the zone with increased fracturing intensity is greatest in and around the middle of stepover structures between strike-slip fault segments. The relative number of low-medium angle fractures is also highest in these zones. These results may be helpful in better interpretation of three-dimensional seismic data and especially improve target selection, well trajectory design, and reservoir modeling in fractured reservoirs controlled by strike-slip faults.

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Seismic response to geodynamic processes and magmatism in the southern part of the Tyrrhenian Sea

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Keywords: geodynamic modelling, seismic modelling, magmatism.

Back-arc basins are the consequence of extensional processes following subduction. The existence of continental crust within these basins is due to complex interactions, involving both mantle convection and crustal deformation. The Tyrrhenian basin is a key laboratory to study mixed oceanic-continental settings and associated volcanism. Here, I will present thermo-mechanical models of the evolution of the basin and the associated magmatism, with primary focus on defining the theoretical present-day seismic responses to their structures. These simulation couple geodynamic codes specifically designed to tackle lithospheric magmatism and wave equation modelling performed in the same grids defined by geodynamic simulation. The result is a set of synthetic waveforms that provide constraint on structure and composition of the basin and surrounding volcanoes.

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Linking fluid temperature and fault kinematics in Picos de Europa (NW Spain)

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Keywords: clumped isotope geothermometry, fault reactivation, brittle deformation, Alpine orogeny.

The Picos de Europa region in NW Spain is mainly composed of Bashkirian-Moscovian limestone units formed in the foreland of the Variscan orogen. NW-SE-trending high angle faults in this limestone massif may date back to the Permian, meaning the time of the latest Variscan deformation, and record a complex reactivation history. The area was located west from the Basque-Cantabrian basin during the period of Mesozoic extension, and later constituted the western realm of the Cenozoic Alpine orogen in N Iberia. Since structural inheritance obscures the relation between the orientation of the stress field, reactivated faults and slip directions, adscribing kinematic indicators to specific deformation events is not straightforward.

Clumped isotope geothermometry has been applied to syntectonic calcite precipitates related to different activity periods of the San Carlos fault system, a NW-SE-striking structure of kilometric scale. These synkinematic samples include slickenfibres on the master fault and associated Riedel shear surfaces, as well as fault-related veins and breccia cements.

Carbonates formed before the Alpine orogeny register temperature values as high as 234-274 ºC, which can be either real or apparent, since the clumped isotope signature is susceptible to resetting under certain circumstances. The calcite components originated during the Alpine shortening record original precipitation temperatures: slickenfibres on segments of the master fault and synthetic Riedel shear surfaces mostly formed in the range between 5-64 ºC; slickenfibres on antithetic Riedel shear surfaces and veins at a high angle to the fault zone formed at 65-99 ºC; and a breccia cement precipitated at 68-79 ºC. The relatively high temperature of samples from the last two groups suggests an earlier precipitation time, since the Alpine deformation induced progressive exhumation, with the consequent decrease in host rock temperature through time. The sense and precipitation temperature of slickenfibres suggest a general dextral strike-slip displacement along the San Carlos master fault during the Alpine orogeny, when deformation involved brecciation and cataclasis.

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Brittle vs. ductile deformation in the Western Ionian Basin: insights from seismic reflectors pattern and sequential restoration methods

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Keywords: Hyblean-Malta Escarpment, ductile deformation, offshore seismic investigation, restoration.

A narrow Plio-Quaternary extensional turbidite basin occurs offshore eastern Sicily, between the Malta Escarpment and the Calabrian Accretionary Wedge. The basin lays between two active faults systems: 1) the normal, E-dipping Malta Escarpment (MESC) system to the West, and 2) the sub-vertical, dextral strike-slip Alfeo Fault system to the East. The fault systems have controlled the Pliocene-Quaternary evolution of the basin. Seismic data interpretation reveals that during the Pliocene the turbidite basin undergone localized subsidence mainly along its easternmost edge where internal reflectors diverge from a structural high. Sequential restoration allowed discriminating two deformation processes in the area: 1) a regional extension controlling the early activity of the MESC faults, and 2) a diffuse prevailing horizontal extensional strain in the lower Pliocene. This latter finding suggests that deformation was likely controlled by lateral migration of a pre-Pliocene ductile layers. Ductile layers can be associated with the presence of underlying salt levels (Messinian), even though clayey or fluid-rich serpentinite levels cannot be ruled out considering diapiric intrusions in the neighbouring areas. Analogue sandbox simulations of progradational sediment over ductile layer show how such a material can flow away due to sediment load, resulting in local subsidence and uplift with the consequent formation of withdrawal basins and highs (see Rojo et al., 2020). Sub-circular highs and basins, comparable to analogue models, were reconstructed for the area by modelling the morphology of the Messinian top-surface. Moreover, differential sedimentary load caused by directional sediment supply from the north is suggested by the sediment waves pattern detected along a seismic line running longitudinally to the turbidite basin. Following these evidence, basins and highs in the Western Ionian Basin have been associated to ductile flow in the pre-Pliocene units favoured by the increasing load of directional sediments since the Pliocene. In addition, withdrawal basins developed adjacent to the MESC faults and right where the higher fault-throws have been measured (see Gambino et al., 2021). This aspect indicates that local thickening of sediments in the hanging-wall blocks of the MESC system (segmented during the Pliocene) played a significant role in the migration process. As evidenced by the Quaternary sub-horizontal seismic reflectors, the ductile deformation vanished in the upper Pliocene whereas brittle deformation continued on the MESC faults up to the present-day.

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Semi-automated fault extraction and quantitative structural analysis from DEM data of the Magadi and Natron basins, East African Rift System

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Keywords: East African Rift System, quantitative structural analysis, fault mapping, semi-automatic method.

Continental rifts show surface expressions of deep crustal processes, such as faulting and volcanism. The East African Rift System (EARS) is one of the most prominent examples of an active continental rift driven by tectonics and magmatism. Nonetheless, we still struggle to quantify the amount of extension due to these processes on a kyr- to Myr-time-scale. In particular, the distribution of extension within low-offset normal fault networks within rift basin interiors is challenging to determine.

To address these issues, we develop a semi-automated workflow to extract normal faults from the TanDEM-X science EM data (12 m horizontal resolution, 0.4 m average height error) of the Magadi- Natron Region of the Eastern branch of the EARS, limited to the north by the Suswa caldera (1.15°S) and to the south by Gelai and Oldoinyo Lengai volcanoes (2.75°S). This data allows us to quantify brittle surface deformation that occurred since the last deposition of widespread volcanic lavas in these basins. Our workflow consists of four main steps: (1) smoothing, (2) Canny algorithm, (3) skeletonization, (4) network classification. The DEM contains different types of noise, which we reduce using Gaussian smoothing. Then we use the Canny edge detection to highlight topographic discontinuities, such as faults. These edges are simplified in single pixel wide lines through the skeletonization algorithm. Finally, we create a network consisting of nodes and edges from this skeleton. After a few post- processing steps, we obtain a fault network, which describes the architecture of the fault system in the Magadi and Natron basins accurately when we compare our results (e.g. elevation profiles, fault length distributions) to previous studies.

A strike analysis applied on the fault data of the whole basin shows four main directions from distinct fault populations. Each direction cluster corresponds to a geological trachyte layer and thus a time interval. For example, the azimuth N20°, corresponds to present and recent rift direction, mostly on the ~1Myr old Magadi trachyte. A direction of N170° is mostly represented in earlier, Mio- Pliocene volcanic units of the rift. Moreover, we derive the fault displacement distribution throughout the basin. This allows us to calculate the total orthogonal extension of each geological unit and to compute the overall amount of extension of the region during geologically recent times.

We thus provide a new high-resolution fault map that depicts strike direction and throw even of small-offset normal faults (from 1 to 150 m). This characterization helps us increase our understanding of recent brittle deformation within the Magadi and Natron basins and thus the propagation of rifting in the eastern branch of the East African Rift System.

Introducing the Iberian Evaporite Structure Database (IESDB)

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Keywords: evaporite, database, tectonics, geo-resources, geoenergy.

Evaporites have unique physical and mechanical properties that make them very different from other sedimentary rocks. Their ability to flow in a viscous manner under relatively low stresses results in the formation of structures, such as diapirs and detachment levels, that control the evolution of many sedimentary basins and orogens. Flow of evaporites typically leads to faulting and folding of the encasing rocks, thus creating traps for hydrocarbons. Moreover, subsurface evaporite structures are preferentially used as repositories for Geo-Energy applications, such as for storing hydrogen, captured CO2 or natural gas injected, and have also been proposed as potential repositories of nuclear waste. In addition, some evaporite minerals are key resources for products like gypsum and potash, and contain critical elements such as Lithium. Accordingly, evaporite structures have been studied for decades, and their accurate characterization is nowadays key for societal challenges such as the Energy Transition. Due their economic importance, vast amounts of surface and sub-surface information about (among others) their structure, stratigraphy, geochemistry or petrophysics have been generated by earth scientists, mining and exploration companies, and geological surveys. However, these data are often not well organised and widely disseminated (i.e., in unconnected databases, scientific articles, unpublished reports, theses, etc.).

Here we present the Iberian Evaporite Structure DataBase (IESDB), the first comprehensive record of evaporite structures developed in any region of the world. The IESDB stores systematically-organised information of undeformed evaporite sequences, salt diapirs, evaporite-cored anticlines, evaporite-detached thrusts and allochthonous evaporite bodies within the Iberian Peninsula and the Balearic Islands. It includes information about the stratigraphy, structure, event chronology, seismic and well data availability, and mining activity of 150 structures, and it is sourced from different thematic data repositories and more than 1,500 published and unpublished research articles, books and book chapters, conference abstracts and industry reports. The IESDB follows the FAIR principles of database management (Findable, Accessible, Interoperable and Reusable) and is presented as an open access webpage where indexed structures can be easily selected from a map or filtered by a multi criteria search engine (www.ub.edu/iesdb). The IESBD aims to be a dynamic useful resource for earth science teaching (i.e., providing examples of exceptional evaporite-related outcrops), academic research (i.e., identifying knowledge gaps on specific structures or regional tectonic settings) and resource exploration and appraisal (i.e., representing a starting point for site election and suitability assessment). The framework established by the IESDB is an opportunity to boost the scientific research on evaporites and to take advantage of their scientific and economic potential. Broadly, Mesozoic Iberian evaporites can be found as nearly circular diapirs within the Basque-Cantabrian and Algarve basins. In other sectors, such as the Lusitanian basin, the Southern Pyrenees and the Betic System, the halokinetic structures of Mesozoic and Paleogene evaporites have been overprinted during the Alpine compression, and they are found nowadays as detachment horizons, anticline cores and allochthonous evaporite bodies. Neogene to Quaternary evaporites remain practically undeformed and are only present within the Duero, Ebro and High Tagus foreland basins, as well as in the (minor and more restricted) basins of the Betic System.

Structural analysis of giant quartz veins from the Eastern Pyrenees (SW Europe)

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Keywords: giant quartz vein, geological mapping, Pyrenees.

Quartz veins with widths ranging from meters to hundreds of meters and lengths from tens of metres to kilometres, known as Giant Quartz Veins (GQVs), Quartz Reefs or Quartz Lodes, are ubiquitous in different tectonic settings worldwide. These structures can act as conduits or barriers to heat and mass transfer within the Earth's crust, are often related to hydrothermal ore deposits, and hold key information about the kinematics of deformation and the geochemical history of their host rocks. However, there are still several open questions on the origin and significance of GQVs, such as their formation mechanisms, the sources of such large amounts of silica and the tectonic and geochemical control(s) on their emplacement. The decrease in silica solubility that enhances quartz precipitation has been classically linked to T-P variations that take place during or after fluid flow. Therefore, the structures that drive that fluid flow are key to envisage the tectono-thermal constrains for meeting a "GQV window".

The Pyrenees is a well-studied Alpine fold-and-thrust belt of in SW Europe that exposes at least 741 GQVs at different structural levels and thus emplaced along different brittle and ductile regional-scale structures. An overall orogen-scale assessment of such outcropping GQVs can be found in the GIVEPY (GIant quartz VEins of the PYrenees) database (https://givepy.info). Here we present the results of detailed fieldwork at three selected areas from the Eastern Pyrenees where GQVs are exceptionally well exposed: the Roc de Frausa, Cap de Creus and La Cerdanya areas. For each area, we first describe the main stratigraphical and structural features of the host rocks and then examine the occurrence of GQVs on the basis of their macrostructure, texture, and deformation structures, in order to address the relationship between GQVs, their host rocks and the regional brittle and ductile dominant structures. These study areas record different grades of deformation and are good examples of several settings where GQVs are emplaced in different host rocks: (1) Upper Cretaceous sedimentary rocks at the Masarac-Vilarnadal sector (Roc de Frausa), (2) Late Carboniferous-Early Permian granitoids and late Neoproterozoic–Early Palaeozoic low-grade metasediments and metavolcanic rocks in the Roses sector (Cap de Creus), and (3) Late Neoproterozoic–Early Palaeozoic low-grade metasediments at the Ger-Gréixer sector (La Cerdanya area). The studied GQVs concentrate along previous brittle and ductile structures such as thrust faults, fold limbs and shear zones, and are linked to a strong alteration "halo" by means of silicification of the adjacent rocks. Data presented contributes to grasp into the structural constraints that drive the formation of GQVs, as well as to improve the knowledge on the surficial geology of the study areas.

Mesozoic stress cycles in the wedge between two collision events

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Keywords: stylolites, stress inversion.

We investigated Mesozoic sequences of the Franconian Platform (SE Germany) according to their deformation history. Based on field observations we performed fault-slip and stylolite stress inversion we could distinguish two stress cycles in an intraplate compressional setting. The first caused by the Europe-Iberia-Africa collision in Late Cretaceous. The associated stress fields show (i) NE-SW directed normal faulting, (ii) NE-SW directed thrusting with a first set of tectonic stylolites and finally (iii) a strike-slip regime with NE-SW compression. The second cycle is induced by the Cenozoic Alpine orogeny and comes with (i) NW-SE normal faulting, followed by (ii) oblique normal faulting to strike-slip faulting with compression in NW-SE direction and a second set of tectonic stylolites. In addition, we can zoom into the transition between the thrusting and strike-slip regime of the first cycle by the preservation of a stress field with none principal stress being in the vertical axis.

With our work we contribute to the understanding of stress development in intraplate compressional settings.

Seagap fault: example of a large-scale long-lived crustal structure, west Somali basin, offshore Tanzania

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Keywords: transcurrent fault, east African rift, subsurface geology, seismic interpretation.

The Tanzania continental margin still represents a geologically poorly understood area, originating from the overlap of two rifting episodes: (1) the Mesozoic N-S divergence between East Africa and Madagascar, which led to the opening of the West Somali basin floored by Mesozoic oceanic crust; (2) the Oligocene to recent E-W divergence between the Somalian Plate and the Rovuma Microplate in the framework of the East African Rift System (EARS) (Stamps et al., 2020). Within this context, deep seismic data across offshore Tanzania suggest this area is characterized by three major sets of regional-scale tectonic systems: (1) the Davie Fracture Zone (DFZ), and associated Davie Ridge, which represents a major transpressional structure of about 2000 km in length (Heirtzler & Burroughs, 1971); (2) the Seagap (or Sea gap) fault, an enigmatic structure interpreted as a 400-km-long crustal fault affecting the Tanzania margin, which parallels the DFZ and together with it retrace the lateral Mesozoic Continent-Ocean Transition; and (3) a set of more recent extensional faults, which orientation spans from NW-SE to N-S (Coffin & Rabinowitz, 1987). Using 3D seismic reflection data and exploration wells, in this contribution we reconstruct the evolution of the Seagap fault system, from the late Eocene to present day. We show that the Seagap fault is composed by large scale faults affecting the seafloor and displaying growth geometries across most of the post Miocene sediments. Its kinematic is expressed through the sequence of releasing and restraining bends dating back at least to the early Neogene. Seismic sections and time slices indicate those restraining bends are generated by the strike-slip reactivation of previous Cretaceous to Eocene faults. By the late Neogene, the Seagap switches to a normal kinematic, as testified by the structures visible at the seafloor. The continuous tectonic activity evidenced by our seismic maps, including 2D deep seismic data from the literature, suggests that by the Middle-Late Jurassic till 125 Ma, the Seagap fault acted as a regional transfom structure parallel to, and initially coeval with, the dextral Davie Fracture Zone. After the cessation of the seafloor spreading, the Seagap fault survived to the Davie Transform activity as a strike-slip fault being still active. We then discuss the Seagap fault geological and kinematic significance through time and it's role in the framework of the East African rifting.

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Wrinkle ridges and other structures related to the Deuteronilus shoreline in Utopia Planitia, Mars

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Keywords: Wrinkle ridges, paleshoreline, Utopia Planitia, Mars.

Some authors suggest that the north of Mars could have hosted an ancient ocean (approximately 3,700 million years ago). Ivanov et al. (2017) delimited the Deuteronilus shoreline differentiating 2 zones; the coast would be -3.9 km from the datum in the Tempe-Crhyse-Acidalia-Deuteronilus regions; and at -3.5 km elevation in the Astapus-Utopia-Elysium regions. In this work we focus on the Utopia region to identify deformation structures that could be potentially related to the paleoshoreline, which shows a curved geometry in plan view, roughly striking NW-SE in the western sector and E-W in the SE. The most conspicuous structures in the mapped area are wrinkle ridges appearing along almost the entire Astapus-Utopia rim. These are one of the most common structures on Mars and are interpreted as compressional reverse fault. We analyse in detail 24 of these wrinkle ridges to obtain their typology, orientation and vertical slip. Most of them correspond to the arch ridge type (Andrews-Hanna, 2020) and present average vertical slips of around 100 m. The angles between wrinkle ridges and the paleoshoreline range between 55 and 120º (measured clockwise from the paleoshoreline trace), although most of them are close to orthogonality (highest frequency in the 85-105º interval, mean angle of 88º and median of 90º). Interestingly, these values are similar in both, south-eastern and western, sectors of the Utopia paleoshoreline, suggesting that this major feature determines, to some extent, the orientation of the analysed wrinkle ridges. Although Utopia Planitia is an ancient large impact basin, the structures associated with an impact rim are usually parallel to the rim rather than orthogonal, as shown by the analysed wrinkle ridges. One possible explanation is that the regional stress field responsible for the wrinkle ridges would have become locally reoriented in the vicinity of the mechanical crustal discontinuities coinciding with the paleoshoreline (Homberg et al., 1997) favouring the orthogonality of the resulting wrinkle ridges. Other interesting structures in the mapped area include pit chains and a penetrative, low-lying cartographic lineation with a consistent NNW-SSE azimuth.

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Morphological Characteristics and properties of Hydrothermal Breccia

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Keywords: hydrothermal, breccia, tectonic, dissolution.

Breccias are rocks composed of fragments or clasts of broken rock in a matrix of finer clasts and/or cement of precipitated minerals. They form either by sedimentary, tectonic, igneous and fluid-flow processes, or a combination of them. Apart from their significance for fundamental research, breccias are very important host rocks for ore deposits, and can also be zones of high permeability and thus serve as potential aquifers. One problem is that it may be difficult to determine what the origin of breccia actually is, especially in terms of the genetic and/or textural classification of tectonic, hydrothermal and dissolution breccias. Improved definition of the diagnostic signature of the individual breccia types requires better knowledge of the relationship between brecciation mechanisms, as well as their genetic associations and geological setting.

Here we analysed the clast geometry and size distribution of a number of known hydrothermal breccias: breccias associated with dolomitising fluids at Pozalagua (North Spain), ore-related breccias from the Black Forest (Southwest Germany) and breccias from the hydrothermal mega-breccia of Hidden Valley (South Australia). Clast sizes in all cases tend to follow a power-law distribution, but power-law exponents can vary significantly, even within a single setting. It is suggested that this may be due to the progressive disintegration of the rock, from an initial mosaic pattern towards floating and rotated clasts, which requires significant dilation and/or dissolution.

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Exploring fault patterns from the interpretation of high-resolution three-dimensional seismic reflection data

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Keywords: fault interpretation, 3D seismic reflection data, fault shapes.

The interpretation of high-resolution three-dimensional (3D) seismic reflection data attempts to determine the real shape of faults at depth. However, fault interpretation methodologies generally include under sampling and smoothing, generating simple planes. In this framework, how much fault information is lost during interpretation? And how this simplification compromises the true geometry of faults and connectivity of fault segments? Here, we interpreted faults using a high-resolution seismic volume. Under sampling was avoided and faults were tracked using time-slices through a 3D coherence volume. This assumption was calibrated using vertical sections. The interpretation of each time-slice generated set of polylines that were connected through the volume to construct fault surfaces. The results were highly corrugated fault surfaces. At this point, we tried to answer if these corrugations are true fault irregularities, or they are image artefacts. Afterward, corrugated surfaces were smoothed by the application of alpha-shape algorithm. The best fit plane for each polylines set was also obtained to analyse. We discuss the uncertainty in identifying realistic fault patterns using high-resolution 3D seismic data.

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A protracted and multiphase transition of the Cadomian active margin to a failed rift setting in northern Gondwana

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Keywords: active margin, passive margin, protracted transition, anisotropy of magnetic susceptibility, Gondwana.

The late Ediacaran to early Cambrian margin of northern Gondwana is a particularly informative setting to study the mechanisms of transition from active/accretionary to passive continental margins without collision. Different interpretations have explained the causes of this transition in northern Gondwana, including ridge–trench–transform interaction, slab break-off, slab-pull force, upwelling mantle plume, or roll-back of the subducted oceanic plate. Hence, the timing, style, and kinematics of this transition still remain unresolved. The Teplá–Barrandian and Moldanubian units of the Bohemian Massif are examined here as an example since they provide a prominent and well-preserved record of Cadomian accretionary orogeny followed by Cambro-Ordovician rifting. A combination of structural data from plutons and sedimentary basins, anisotropy of magnetic susceptibility (AMS), and U–Pb zircon geochronology suggests that the active to passive margin transition in northern Gondwana was prolonged and involved several superposed phases. First, the Cadomian subduction was terminated by slab break-off at ca. 527 Ma and, subsequently, resulted in a temperature rise to cause calc-alkaline plutonism between ca. 524 and 522 Ma in a dextral transtensional regime. Second, the upper crustal extension continued and led to the development of sedimentary basins filled with thick successions of fluvial to marine deposits with intermittent volcanic activity between ca. 515 and 499 Ma. Third, felsic magmatism related to basaltic underplating occurred at ca. 490–480 Ma, correlative with the 'Ollo de Sapo' event in Iberia. Fourth, the end of felsic plutonism was replaced by basaltic submarine volcanism recording decompression mantle melting at around 470 Ma. Finally, the quiescence of submarine volcanic activity was followed by rapid basin subsidence at ca. 458–452 Ma. In conclusion, the above described protracted, multi-phase transition is interpreted as reflecting lower lithosphere break-up before upper lithosphere and was associated with failed rifting in the eastern segment of the former Avalonian–Cadomian belt.

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S5.

Mountains building & geodynamics

CONVENERS & CHAIRPERSONS

Bons D. Paul (University of Tübingen)

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Strain decoupling across the western front of the Alboran domain thrust sheet (Western Gibraltar Arc)

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Keywords: accommodation folds, crystalline thrust sheet, decoupling.

In the Western Gibraltar Arc (WGA) the two main components of the Alboran domain –the Malaguide and Alpujarride complexes- form a single, large-scale, crystalline thrust sheet (the Alboran thrust sheet or ADTS). The ADTS is thrusted upon the Frontal Units and the inner part of the fold-and-thrust belt, which exhibits a typical thin-skinned tectonic style. In this work, we explore the early-middle Miocene, deformational characteristics of the ADTS emplacement in the northern (Betic) branch of the arc, and compare them with those of the overthrusted units.

In the northern part of the WGA, the ADTS crops out as a continuous sheet bound below by a major hangingwall ramp at its western front. This ramp cuts up towards the west both the Alpujarride complex, which includes a thick (up to 4,5 km) peridotite slab at its lower part, and the Malaguide complex on top of the ADTS. Initial thickness of the ADTS should be between its current one (11 km) and the thickness inferred through prevailing late metamorphic conditions during its emplacement (12,5-16 km). Coeval deformation is moderate and consists of N-S to N020ºE accommodation folds developed above the frontal hangingwall ramp and N-S upright folds in the rear part of the sheet. Physical conditions during the development of folds above the peridotite unit range between non-metamorphic conditions (T < 200ºC) in the upper part of the Malaguide complex to low grade metamorphism (300ºC < T < 550ºC) in the lower Jubrique Unit sequence (Alpujarride complex, on top of the peridotite slab). For the same event, we obtain conditions of T= 550º-620ºC and Pmax = 3,5 kb in schists and amphibolites located at the bottom of the peridotite slab. The structural record and the inferred temperature range indicate both that the peridotite behaved essentially as a rigid body during the ADTS emplacement and that, despite its considerable thickness, the ADTS developed as a relatively low strained thrust sheet.

Kinematics of the frontal accommodation folds and upright folds indicate a tectonic transport direction of the ADTS towards N280ºE. However, transport directions in the overthrusted Frontal Units and in the fold-and-thrust belt vary from N280ºE to N320ºE. This variation, which fits well with the outward divergent thrusting pattern of progressive arcs, also indicates a high grade of decoupling between the ADTS and the footwall units. Strain decoupling also occurs among the footwall units as supported by the abrupt change in tectonic style between the frontal and rear parts of the overthrusted Frontal Units (imbricate fan structure *vs* highly strained duplex) and the typical thin-skinned style in the fold-and-thrust belt.

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Are collision mountain belts amplifications of pre-orogenic crustal-lithospheric heterogeneities?

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Keywords: inversion, structural inheritance, orogeny.

The aim of this presentation is to spark discussion pertinent to how we move up and down scale in the interpretation of deformation processes – and the question in the title is largely rhetorical. The concept of the Wilson Cycle has at its centre the notion that mountain belts are born from rifted continental margins, that themselves developed from lithospheric extension acting on former orogens. Within intra-continental rift basins, normal faults are commonly reactivated as reverse faults when these basins experience weak contractional deformation (inversion tectonics). The significant partitioning of deformation across the India-Asia collision system can be explained by the strength of these lithospheres at the onset of collision, themselves products of their individual geological histories. And it is well-established that the pre-collision structures of Alpine-type orogens, inherited from when these regions formed rifted continental margins, have influenced the progression of contractional deformation and the thermo-barometric evolution of their constituents. Just as the propensity for crystalline plasticity in minerals need not be defined by properties of perfect crystals, but rather by the behaviour of lattice defects, so too during orogenesis, deformation may be governed by heterogeneities inherited and embedded within the converging lithospheres. The challenge then is to unravel the patchwork of pre-orogenic heterogeneities if we are to understand the progression of individual orogenies. There are significant uncertainties associated with these endeavours and it is important to challenge orthodoxies, many of which are built upon overly simplistic, early adoptions of concepts rather than on substantial evidence. Examples are drawn from the Alpine and Apennine-Maghrebian orogenic system. While orogeny has progressed through the Tertiary, the geological history inherited from end-Variscan (Permian) times has been important. Late Variscan mafic intrusions has promoted transient subduction (and related return, channel-flow) in the Alps. Major rifting events, associated with the formation of western arms of Tethys, created a patchwork of rift basins, hyperextended continental lithosphere, identified from their syn-rift and post-rift strata. These in turn have exerted a first-order control on the geometry of crustal shortening in the Alps and Apennines. But perhaps as deformation, and associated deformation conditions, evolve, the importance of structural inheritance wanes: at what stage do orogenies become "self organised"? And at what length-scales are inherited lithospheric weaknesses important? Understanding these large-scale sensitivities are important if local structures and their forming processes are to be appropriately deduced.

Dating the halokinesis at the frontal structures of the Serres Marginals Thrust Sheet: first results from Les Avellanes area, NE Spain

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Keywords: salt tectonics, Pyrenees, diapirism, Les Avellanes diapir, Serres Marginals.

The Pyrenean fold-and-thrust belt (F&TB) is the result of the reactivation of an inherited passive margin with salt structures. The continuity and thickness of the salt layer, and the inherited salt structures were critical during the contractional evolution and controlled the resulting structural style. In this sense, the frontal part of this F&TB is characterized by a thin Late Triassic-Paleogene cover strongly deformed by thrusts and tight folds pierced by diapirs of Upper Triassic evaporites that extrude locally forming salt sheets. Understanding these structures requires analyzing both the role of salt in their development and timing. In this contribution we present tectonostratigraphic and structural data used to suggests a preliminary model for the development of those frontal salt structures related to orogenic formation. At the external part of South-Central Pyrenean wedge, in the western area next to Les Avellanes diapir, there are two SE-NW synclines separated by a thin strip of Triassic (Keuper) salt whose contact evolves longitudinally into a back-thrust. Those synclines are detached over the Triassic layer and are formed by a bottom, relative thin, pre-orogenic Mesozoic succession followed by an upper, synorogenic sequence Ypresian to early Oligocene in age. The Ypresian is represented by syntectonic limestones thinning across fold limbs toward structural highs where syntectonic unconformities are also interpreted. Early Oligocene clastic-evaporite sediments, deposited at the hinge of the syncline folds, unconformably overly the Ypresian limestones while onlap the Triassic salt unit between both synclines with a thinner and uncomplete sequence. These relationships suggest that salt migration and the related deformation was linked to the onset of shortening at the area. During the Ypresian, contractive deformation at the external parts of the F&TB started with the development of salt-cored anticlines. While increasing shortening, limb rotation took place and salt pierced through the eroded crests of anticlines forming syn-compressional diapirs during the early Oligocene. Salt-sediment interaction was recorded in the form of growth strata and internal unconformities by the early Oligocene sequence. Contraction peaks in the late Oligocene, when diapir growth finished after secondary welding. Further shortening was accommodated by reactivation of welds as back-thrusts. The proposed model supports diapir development coevally to the propagation of contractional deformation at the outer parts of the F&TB during Eocene-early Oligocene times.

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Fluid flow at the base of Variscan thrust sheets in the Cantabrian Zone (NW Iberia)

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Keywords: Cantabrian Zone, fluid flow, stable isotopes, thrust-related deformation, fault rocks.

The Cantabrian Zone constitutes the foreland and thrust belt of the Variscan Orogen in the NW Iberian Massif. Deformation was accomplished through the emplacement of several thrust units with associated folds during the Moscovian (Pérez-Estaún et al., 1988). The E–W trending León Thrust, a major out-of-sequence breaching structure, duplicated several of the palaeogeographic domains around the Moscovian-Stephanian boundary (Alonso et al., 2009). The Cantabrian Zone occupies the core of the Ibero-Armorican Arc, a large-scale curvature of debated origin. Recent N–S Alpine convergence contributed to fold tightening and reactivation of favourably oriented earlier faults (Alonso et al., 1996). The Variscan thrust sheets, with a variable thickness in the order of 4–6 km, display at their base thin (0–2 m thick) shear zones that contain cataclasites and ultracataclasites with evidence of pressure solution, hydrofracturing and vein precipitation.

We have investigated C and O stable isotopes in the basal shear zones formed by carbonate-derived fault rocks in order to constrain the fluid flow during the emplacement of thrust sheets in the Variscan Orogeny. Fragments and matrix of cataclasites, calcite slickenfibres and calcite cements of clastic injections retain $\delta^{18}O$ and $\delta^{13}C$ isotopic ratios typical of the precursor formations involved in the shear zones, whereas thicker tensional veins subperpendicular to the shear zone boundaries display an enrichment in ^{16}O. This suggests that the carbonate shear zones behaved as a system closed to the infiltration of externally derived fluids, and the pore fluids were in isotopic equilibrium with the fault rock assemblages during deformation. Partial fluid exchange with organic carbon-rich footwall lithologies is sometimes suggested by a slight depletion in ^{13}C in the fault rocks while maintaining typical $\delta^{18}O$ values. The opening of tensional veins during subsequent deformation in the Cantabrian Zone opened the system to the infiltration of externally derived fluids that were not buffered by the precursor formations, most likely of meteoric origin given their lower $\delta^{18}O$.

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Strain partitioning at the active mountain front of the western Betics (southern Spain)

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Keywords: active tectonics, focal mechanisms, progressive arcs, southern Iberia.

The outer mountain front of the western Betics (southern Spain) is located at the limit of the fold-and-thrust belt, which deforms the Mesozoic-Paleogene sedimentary cover of the Iberian paleomargin, and incorporates also tardi-orogenic, post-Serravalian sedimentary units of the foreland basin. In contrast with conventional mountain fronts defined by highly continuous foreland-dipping monoclines controlled by thrusts, the western Betics mountain front is non-cylindrical and appears segmented into two kinematically distinct domains. The structures of the eastern domain are compatible with an ENE-WSW strike-slip dominated dextral transpressional zone (the Algodonales-Badolatosa shear zone, ABSZ). These include essentially brittle, strike-slip faults with associated Riedel-type conjugate systems and, affecting gypsum-rich marly Triassic units, ductile transpressive zones with boudinaged and clockwise rotated dolostones bodies. The ABSZ is the northernmost map-scale structure of a wider transpressional sector of the fold-and-thrust belt that constitutes a transitional recess between two salients with mainly thrust tectonics (Expósito et al., 2022). To the NW of the ABSZ, the mountain front draws an arcuate shape and is dominated by NW-vergent thrusts. Several transpressional and shortening structures along the western Betics mountain front eventually affect post-Tortonian units and control to some extent the evolution of the drainage system (river courses and catchments, endorheic systems, etc.). Focal mechanisms of nine earthquakes ($M_w \geq 3.8$) occurred in the region were obtained via FMNEAR method based on the waveform inversion and the linear finite source model (Delouis, 2014). All earthquakes are shallow (< 10 km) and their kinematics are compatible with surface structures. Three earthquakes along the location of the ABSZ are compatible with dextral displacement on NE-SW/ENE-WSW slip planes. Five earthquakes concentrated on the NW corner of the study area suggest NW thrusting on SE-dipping planes. One earthquake is related to dextral displacement on a NW-SE (Riedel) plane.

In conclusion, our field and seismological analysis suggests that the western Betics mountain front is still active and its deformation is partitioned into transpressional and thrust tectonics. The origin of such strain partitioning could be (1) the evolution of the Betic fold-and-thrust belt under progressive arc kinematics, (2) the shallow expression of major structures affecting the basement (Expósito et al., 2022), or (3) a combination of both.

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Contrasting orogenic grain and kinematic patterns along the Betics fold-and-thrust belt as potential expression of deep-seated mechanisms

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Keywords: Gibraltar Arc, STEP fault, orogen-parallel extension, decoupling.

In the northern branch of the Gibraltar Arc, the orogenic grain of the central and western Betics external fold and trust belt (FTB) draws two secondary arcs, connected by a salient-recces transition segment, whose southernmost limit is defined by the Torcal shear zone (TSZ). The central FTB salient is defined by WSW-ENE to W-E thin-skinned shortening structures involving post-Burdigalian, syn-orogenic sequences in its deformation front. Thrust surfaces are dominantly SE to S-ward dipping and slickenlines suggest NNW-SSE to N-S transport directions. At the SW end of this salient, just east of the TSZ, the shortening structures trend becomes N-S. The westernmost FTB salient, within the Gibraltar Arc hinge, is composed of NW to W-ward verging, shortening structures with radial transport direction. Both salients are linked by the abovementioned transitional domain an E-W to ENE-WSE transpressive band, dominated by dextral strike-slip. This transpressive zone is significantly segmented in scattered topographic highs due to a highly localized orogen-paralell extension. These three tectonic domains seem to have been differentiated since the upper Miocene to Holocene suggesting a decoupling between the W-ward migrating hinge of the Gibraltar Arc and the rest of the arcuate chain. Such decoupling would fit well with the existence of a W-E trending STEP fault (Govers & Wortel, 2005), whose easternmost tip were located under the transition between the central and western Betics. Thus, the dominantly dextral, significantly stretched TSZ, located just north of the betic FTB/hinterland boundary, would be the expression in the FTB of such deep STEP fault. In this context, the recent FTB deformation in the central Betics would respond to the current NW-SE shortening undergone by the Iberian Peninsula, whereas the kinematic features of both the transitional transpressive band and the westernmost FTB are consistent with a WNW-ESE directed far field vector associated with the arc westward migration. Interestingly, the recent intraplate deformation in the Betics foreland has produced greater relative uplifts in front of the central Betics, mostly accommodated in overall WSW-ENE faults, than in westernmost sectors. Additionally, the kinematics of reactivated structures in the westernmost sector of the foreland is compatible with a WNW-ENE convergence. Assuming some amount of mechanical plates coupling along the northern branch of the Betics, these foreland deformation features would agree with the proposed difference in the convergence angle along the central and western Betics FTB.

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Petro-structural mapping of the Palmi shear zone (Calabria), a combined field and aerial-based survey

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Keywords: shear zone, UAV survey, virtual outcrop model, structural-geological survey.

A combined field and aerial-based petro-geo-structural survey have been carried out to investigate the main structures of the crystalline basement of the Tyrrhenian coast of southern Calabria near the village of Palmi where a crustal-scale Alpine shear zone is exposed (Fazio et al., 2017; Ortolano et al, 2020).

In order to reconstruct 3D virtual outcrop models, we adopted a multiscale approach to acquire the spatial orientation of planar and linear structures of sheared rocks by using classical survey techniques as well as Structure from Motion (SfM) techniques and UAV (Uncrewed Aerial Vehicle). This approach allowed us to increase the spatial orientation of structures dataset by also adding virtually collected data (GeoVis3D freeware software), especially from steep inaccessible cliffs along the coastline. The combination of multiple data collection techniques (manual v. virtual) is considered a good and efficient way to increase the statistical meaning of structural datasets in crystalline basement where critical exposures may be preserved on steeply dipping slopes or dangerous/restricted areas.

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Response of drainage pattern and basin evolution to tectonic and climatic changes along the Dinarides-Hellenides orogen

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Keywords: Mountain building process, Tectonic and climate interactions, Drainage basin analysis, Central Mediterranean.

The junction of the Dinaric and Hellenic mountain belts bordering the Adriatic Sea (central Mediterranean) is the site of a trans-orogenic normal fault system (the Shkoder-Peja Normal Fault or SPNF) that has accommodated oroclinal bending, as well as focused basin formation and drainage of the Drin River catchment. We provide new insight on the temporal and spatial scales on which lithospheric deformation (slab retreat, orogenic bending) has interacted with surface and climatic erosion (glacial and fluvial) to induce a drastic reorganisation of river drainage since the Last Glacial Maximum (LGM). Analysis of fluvial morphology of the Drin River system reveals higher values of river slope indices (k_{sn}) and χ (Chi) between the normal faults of the SPNF and the Drin drainage divide. The drainage divide is predicted to be migrating away from the SPNF, except at the NE end of the SPNF system. Two basins analysed in the hangingwall of the SPNF, the Western Kosovo Basin (WKB) and Tropoja Basin (TB), contain flat-lying late Pliocene-to-Holocene sedimentary rocks deposited well after the main fault activity and immediately after the LGM. These sediments document a transition from lacustrine to fluvial conditions in early Pleistocene time that reflects a sudden change from internal to external drainage of paleo-lakes. In the Tropoja Basin, these late- to post-LGM layers were successively incised to form three generations of river terraces, interpreted to reflect episodic downstream incision during major reorganisation of the paleo-Drin River drainage system. New ^{36}Cl-cosmogenic-nuclide depth-profile ages of the two youngest of these terraces (~12 and ~8 ka) correlate with periods of wetter climate and increased sediment transport to the TB in post-LGM time. The terraces yield an incision rate of ~12 mm/yr, an order-of-magnitude greater than those previously reported in central and southern Albania. Taken together, it appears that glacial/interglacial climatic variability, hinterland erosion and base-level changes regulated basin filling and excavation cycles at a time when the rivers draining the WKB and TB became part of the regional river network emptying into the Adriatic Sea. The Dinaric-Hellenic junction hosted these dramatic morphological changes long after the faulting and clockwise rotation on the SPNF and its related normal faults initiated in late Oligocene-Miocene time. The normal faults of the SPNF provided a structural and erosional template upon which climate-induced erosional events in Holocene time ushered in a reorganisation of the regional fluvial drainage pattern, which led to the formation and partial demise of lakes and basins. This major morphological reorganisation is manifested today by the arc of the present main drainage divide around the SPNF, which deviates from the general coincidence of the divide with the NW-SE trend of the Dinaric-Hellenic mountain chain. This first-order morphological feature reflects the structural imprint left by roll-back subduction of the Adriatic slab beneath the northwestern Hellenides.

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Growth and evolution of the Saxothuringian orogenic wedge and its extensional collapse: the Variscan P-T-t record of the metasediments of Erzgebirge, Bohemian Massif

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Keywords: metapelites, Erzgebirge orogenic wedge, thermodynamic modelling, geochronology, Variscan orogeny.

The metasediments surrounding the well-studied *(U)HP* rocks of the Erzgebirge crystalline complex (Saxothuringian Domain, Bohemian Massif) are poorly explored, although they provide an important link between deep subduction and mid-crustal processes. Several transects from the low-grade hanging wall phyllites to the footwall medium-grade micaschists have been investigated to understand Variscan tectonometamorphic evolution of this region. Using field structural geology, thermodynamic modelling and geochronology (monazite U–Pb and mica ^{40}Ar–^{39}Ar dating), we constrained the *P–T* conditions and timing of four deformation events (D1–D4) identified by structural analysis.

The first M1-D1 event is characterized by *HP–LT* minerals (garnet, chloritoid, phengite, paragonite, and rutile) defining the S1 foliation with an M1 peak *P–T* conditions increasing from 13 kbar and 520°C in phyllites to 25 kbar and 560°C in micaschists. The corresponding geothermal gradient of 6–11°C/km is typical for subduction environments. The M2-D2 event corresponds to the deformation and metamorphic overprint of the S1 fabric during partial decompression. The M3-D3 event is mainly developed in micaschists and becomes more intense towards the footwall. It is accompanied by a development of subhorizontal S3 cleavage and formation of *MP–MT* minerals (biotite, staurolite and ilmenite). The M3 event reaches the peak *P–T* conditions of 5–9 kbar and 595°C representing a barrovian-type geothermal gradient of 17–30°C/km. Finally, all metamorphic fabrics were heterogeneously affected by the low-grade M4-D4 upright folding.

Nine samples have been analyzed by monazite LASS ICP-MS geochronology. The phyllites preserve homogeneous ages around 350–340 Ma. In contrast, the micaschists with intense M3 metamorphism record two groups of ages. Few monazite grains in the garnet cores and in the locally preserved M1 matrix are dated to ~340 Ma, while monazites located in the M3 matrix are younger, at ~330 Ma. ^{40}Ar–^{39}Ar geochronology from micas was used to date 16 samples with step-heating and *in-situ* UV-laser ablation. The phyllites revealed ^{40}Ar–^{39}Ar ages ranging between 343–328 Ma, while in micaschists these ages cluster to ~330 Ma. The geochronological data indicate that between 350–340 Ma, at least some phyllites experienced burial and exhumation, while burial of the micaschists is slightly younger (340–335 Ma). The strong M3 metamorphic overprint in the micaschists related to exhumation was dated to ~330 Ma.

The D1-D2 events (350–335 Ma) are interpreted to record the growth of the orogenic wedge while its present-day architecture resulted from a significant vertical shortening D3 associated with barrovian-type metamorphism M3 (330 Ma) which resulted in overall ductile thinning of the wedge. A new tectonic model is proposed, in which the Erzgebirge part of the Saxothuringian Domain reveals a spectacular example of active margin evolving through the formation of accretionary prism towards the building of the orogenic wedge by accretion of subducted continental crust and finally its extensional collapse.

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Subduction, underplating, and return flow recorded in the Cycladic Blueschist Unit exposed on Syros, Greece

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Keywords: subduction channel, exhumation, blueschist, greenschist.

Exhumed high-pressure/low-temperature (HP/LT) metamorphic rocks provide insights into deep (~20-70 km) subduction interface dynamics. On Syros Island (Cyclades, Greece), the Cycladic Blueschist Unit (CBU) preserves blueschist-to-eclogite facies oceanic- and continental-affinity rocks that record the structural and thermal evolution linked to Eocene subduction. Despite decades of research, the metamorphic and deformation history (P-T-D) and timing of subduction and exhumation are matters of ongoing discussion. Here we suggest that the Syros CBU comprises three coherent tectonic slices, and that each one underwent subduction, underplating, and syn- subduction return flow along similar P-T trajectories, but at progressively younger times. Subduction and return flow are distinguished by lineations and ductile fold axis orientations: top- to-the-S-SW (prograde-to-peak subduction), top-to-the-NE (blueschist facies exhumation), and then E-W coaxial stretching (greenschist facies exhumation). Amphibole zonations record cooling during decompression, indicating return flow above a cold subducting slab. Multi-mineral Rb-Sr isochrons and compiled metamorphic geochronology suggest that the three slices record distinct stages of peak subduction (53-52 Ma, ~50 Ma (?), and 45 Ma) that young with structural depth. Retrograde blueschist and greenschist facies fabrics span ~50-40 Ma and ~43-20 Ma, respectively, and also young with structural depth. The datasets support a revised tectonic framework for the CBU, involving subduction of structurally distinct coherent slices and simultaneous return flow of previously accreted tectonic slices in the subduction channel shear zone. Distributed, ductile, dominantly coaxial return flow in an Eocene-Oligocene subduction channel proceeded at rates of ~1.5-5 mm/yr, and accommodated ~80% of the total exhumation of this HP/LT complex.

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High-stress deformation and short-term thermal pulse preserved in the microstructure of exhumed lower-crustal seismogenic faults

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Keywords: pseudotachylyte, lower-crust, EBSD, microstructure, earthquakes.

Earthquake rupture in strong, anhydrous lower continental crust requires high failure stress, in the absence of high pore fluid pressure. Several mechanisms proposed to generate high stresses at depth imply transient loading driven by a spectrum of stress changes, ranging from highly localized stress amplifications to crustal-scale stress transfers. High transient stresses up to gigapascal (GPa) magnitude are proposed by field and modelling studies (Campbell et al., 2020), but the evidence for transient pre-seismic stress loading is often difficult to extract from the geological record due to overprinting by co-seismic damage and slip. However, the local preservation of deformation microstructures indicative of crystal-plastic and brittle deformation associated with the seismic cycle in the lower crust offers the opportunity to constrain the progression of deformation before, during and after rupture, including stress and temperature evolution.

Here, detailed study of pyroxene microstructures characterizes the short-term evolution of high stress deformation and temperature changes experienced prior to, and during, lower crustal earthquake rupture. Pyroxenes are sampled from pseudotachylyte-bearing faults and damage zones of lower crustal earthquakes recorded in the exhumed granulite facies terrane of Lofoten, northern Norway. The progressive sequence of microstructures indicates localized high-stress (at the GPa level) pre-seismic loading accommodated by low temperature plasticity, followed by coseismic pulverization-style fragmentation and subsequent grain growth triggered by the short-term heat pulse associated with frictional sliding. Thus, up to GPa-level transient high stress (both differential and shear) leading to earthquake nucleation in the dry lower crust can occur in nature, and can be preserved in the fault rock microstructure.

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Inversion of a nappe-basement system – a 4D reconstruction

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Keywords: 3D geological modelling, passive margin inversion, cross-section restoration, 4D reconstruction.

Inversion of passive margins and their incorporation into fold-and-thrust belts is a fundamental stage during building of mountain chains. In this study, we selected the local Doldenhorn Nappe and Aar/Gastern Massifs (Central Swiss Alps) system as an ideal laboratory to document the impact of inherited structures, along-strike rheological variations, and basement tectonics on the evolution of a fold-and-thrust belt during continent-continent collision. A multi- methodological approach that combined 3D geological modelling and cross-section restoration allowed us to reconstruct the 4D evolution of the investigated area during the late-stage Alpine orogeny (30 Ma to present). Our results demonstrate that: (i) the Doldenhorn Nappe is the product of the inversion of an asymmetric half-graben basin originally located along the proximal part of the European continental passive margin with a fault-bound complex 3D geometry; (ii) associated lateral variations in incipient basin sediment thicknesses correlate directly with the along-strike variation of the deformation of the Doldenhorn Nappe; (iii) thin-skinned nappe formation mechanisms and the nappe geometries are controlled by aforementioned initial top- basement geometry and by the rheological strength contrasts between basement and cover sediments, while (iv) thick-skinned basement-involved uplift and shortening is on the one hand side controlled by the former basement passive margin geometry and on the other hand side controls itself the late-stage collisional overprint and mechanics of the system. This reconstruction illustrates how the 3D morphology and variability of the sedimentary cover and basement units of a former passive continental margin conditions the mechanism and style of basin inversion during a continent-continent collision, and how this is recorded by the exposed along-strike variations in the tectonic architecture.

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Variable structural patterns along the Irtysh Shear Zone in Central Asia: a result of arc-arc collision at different crustal levels?

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Keywords: Irtysh Shear Zone, Central Asia, arc-arc collision, structural level, deformation styles.

The NW-SE Irtysh Shear Zone represents a major suture zone in the Central Asian Orogenic Belt, which resulted from the Permian collision of the Siberian marginal arc system (Chinese Altai) with the intra-oceanic arc system of the East/West Junggar. I conducted structural analysis along the Irtysh Shear Zone, which shows variable deformation patterns along the strike of the shear zone. Along the western segment of the Irtysh Shear Zone, I recognized two generations of structures with the earlier NE-SW contractional deformation and the later phase of sinistral brittle strike-slip faulting. In contrast, the eastern segment of the Irtysh Shear Zone was characterized by three phases of ductile deformation, with an episode of orogen-parallel extension (sub-horizontal foliation and orogen-parallel NW-SE stretching lineation) occurring after NE-SW contraction, but prior to sinistral shearing. Given the obvious decrease of metamorphic grade along the Irtysh Shear Zone from west to east, I interpret the variable structural patterns along the western and eastern segments of the Irtysh Shear Zone as deformation response of the arc-arc collision at upper and lower crustal levels, respectively. The research outcome demonstrates that the lower crust materials could flow along the narrow collisional zone with the ongoing convergence of two arc systems.

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In shear we "thrust": deformation and temperature variation along a thrust-sense shear zone in the hinterland-foreland transition zone of the Sardinian belt

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Keywords: shear zone, kinematic vorticity, Raman Spectroscopy on Carbonaceous Material, Variscan belt.

In collisional environments, the hinterland-foreland transition zone is characterized by km-scale ductile shear zones linked to thrust-sense shearing, which lead to the formation of thrust sheets or tectonic nappes. Structural investigations at different scales, kinematics of the flow, and finite strain analyses are fundamental tools to determine how deformation is accommodated and partitioned. Nevertheless, the spatial temperature variations can potentially be responsible for the dynamic weakening and strain localization, so establishing the thermo-kinematic state of these shear zones is necessary. The Barbagia Thrust (BT; Carosi & Malfatti, 1995; Montomoli et al., 2018) characterizes the Variscan hinterland-to-foreland transition zone of the Sardinian orogenic wedge. Its thermo-kinematic architecture remains poorly investigated. A combination of structural investigations, at different scales, integrated with Raman Spectroscopy on Carbonaceous Material (RSCM; Beyssac et al., 2002) thermometry along two different transects orthogonal to the BT, reveals a progressive and systematic increase of strain, amount of simple shear, and of RSCM temperature, approaching the core of the shear zone. Although the obtained structural-thermal data across two different sectors of the BT could be interpreted in different ways, our results allow us to discuss the possible occurrence and its role of shear heating along the BT. Integrating different methodologies, we point out how the BT represents a full-fledged tectonic boundary that divides the internal sector of the Sardinian orogenic wedge to the external one and represents a change from hinterland- to foreland-style deformation.

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Tectono-metamorphic evolution of the Briançonnais Units along the southwestern edge of the Alps: Constraints from the Marguareis Massif (Western Ligurian Alps)

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Keywords: HP-LT metamorphism, Briançonnais, Alpine Orogeny, Southwestern Alps.

The Briançonnais Units are regarded as the witnesses of the thinned European continental crust progressively involved in collisional processes starting from middle Eocene age (i.e. Vanossi, 1986; Michard et al., 2004). In the southwestern Alps a SW-verging stack composed of Helminthoid Flysch located in between Briançonnais Units (Sanità et al., 2020) crops out along the southwest sector of the Marguareis Massif (Western Ligurian Alps). The topmost Marguareis Unit (Briançonnais Domain) shows a Meso-Cenozoic sedimentary succession and recorded a deformation history dealing with the overprinting of fold systems (D1-D4 events), the latter developed at different structural levels, and later faults (Sanità et al., 2020). Combining micro-scale structural observations and Chlorite-phengite multiequilibrium thermobarometry on middle Eocene metapelites we reconstruct the Pressure-Temperature-time-deformation path of the Marguareis Unit. Microstructural analysis highlights that only the D1 and D2 events are characterized by metamorphic re-crystallization. D1 event is represented by S1 slaty cleavage marked by preferred orientations of Chl + Phg + Qtz + Alb + K-Fsp + Epd ±Cal whereas the D2 event is testified by a crenulation cleavage outlined by Phg + Chl + Qtz + Alb + K-Fesp ± Cal. D3 and D4 events are associated with stylolitic surfaces without metamorphic re-crystallization suggesting their development at shallower crustal levels. We applied the Chl-Qz-wt, Phg-Qz-wt and Chl-Phg-Qz-wt methods on D1- and D2-related Chl-Phg pairs. The thermobarometric estimations show that the D1-related Chl-Phg couples registered Pressure-peak conditions of 1.00-0.90 Gpa and 280-330°C. The retrograde path of the Marguareis Unit is well constrained by the Chl-Phg pairs re-crystallized during the D2 event at 0.85-0.7 GPa and 230-300°C. So, our results show that the prograde path is not recorded in the Marguareis Unit and the Chl-Phg pairs grown along the S1 and S2 foliations depict its retrograde trajectory. The exhumation already started during the D1 and it continues during the D2 up to the shallower structural levels into the Alpine wedge. Thus, the reconstructed P-T path strongly indicates that the the Marguareis Unit recorded HP-LT metamorphic conditions in a continental subduction setting. The latter was already documented in others sectors of the Alpine belt.

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Structural architecture and kinematics of the Helminthoid Flysch-Briançonnais Units coupling: a key for deciphering the tectonic evolution of the southwestern Alps

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Keywords: structural architecture, Helminthoid Flysch-Briançonnais Units, tectonic evolution, Alpine Orogeny.

The southwestern Alps are characterized by a stack of tectonic units stemming from different paleogeographic domains (Ligure-Piemontese Ocean and European continental margin, Vanossi et al, 1986). This stack consists of the Helminthoid Flysch Unit thrusted onto the oceanic-derived Moglio-Testico Unit and the European-derived Briançonnais Units. The Late Cretaceous non-metamorphic Helminthoid Flysch Unit is detached from its original basement whose nature is debated; the Moglio-Testico Unit represent a fragment of the Ligure-Piemontese oceanic crust implicated in the oceanic subduction; whereas the Briançonnais Units are the witnesses of European continental crust progressively involved a convergent setting starting from middle Eocene age (i.e. Vanossi, 1986). Contrary, at the boundary between Maritime and Ligurian Alps the tectonic stack is characterized by apparent inverted structural relationships, i.e. with the Helminthoid Flysch located in between the Briançonnais Units. The latter are represented by the topmost Marguareis Unit and by the lowermost Cabanaira Unit. Several continental tectonic slices, composed of the same lithotypes of the Marguareis Unit, crop out between the Helminthoid Flysch and the Cabanaira Unit. We investigated this peculiar sector of the belt in order to unravel the tectonic coupling history of the units. Field mapping and micro- to map-scale structural analysis outlined that each unit, and the slices also, recorded different finite strain patterns, mostly dealing with the superpositions of folding systems, developed before their coupling and at different structural levels and time-span (Sanità et al., 2020). The continental tectonic slices show similar deformation patterns to these documented in the Marguareis Unit. After their coupling the units shared the same deformation events. The boundaries between each unit and/or slices are marked by thrust surfaces represented by top-to SW high-strain cataclastic shear zones responsible of their coupling. The structural analysis allowed us to reconstruct a late Eocene-early Oligocene tectonic coupling history during which, firstly the Helminthoid Flysch thrusted onto the already exhumed Briançonnais Units and then the Marguareis Unit overthrust, with an out-of-sequence thrust, onto the Helminthoid Flysch and the lowermost Briançonnais Units, i.e. Cabanaira Unit and the continental tectonic slices. This out-of-sequence thrust is a first-order tectonic feature extending for about 70 km^2 and it is responsible of the inverted structural relationships between the Helminthoid Flysch and Briançonnais Units and it played a key-role in the tectonic evolution of this sector of the southwestern Alps.

Sanità E., Lardeaux J.M., Marroni M., Gosso G. & Pandolfi L. (2020) - Structural relationships between Helminthoid Flysch and Briançonnais Units in the Marguareis Massif: A key for deciphering the finite strain pattern in the external southwestern Alps. Geological Journal, 56, 2024-2040. https://doi.org/10.1002/gj.4040.
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Petro-structural investigations of the HP-LT Quartzite-Phyllite (QP) nappe in the northern Peloponnese, Southern Hellenides, Greece

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Keywords: syn-orogenic extension, Cretan detachment, continental unroofing, Corinth rift, Peloponnese.

Oligo-Miocene high-pressure metamorphic units outcrop immediately south of Corinth rift within the northern Peloponnese metamorphic windows on the footwall of the Cretan detachment. Miocene exhumation mechanisms of these greenschist to blueschist high-pressure units is poorly constrained in northern Peloponnese. In this study, we document the structural evolution of the quartzite-phyllite nappe based on a recent field campaign and micro-structural investigations coupled with RSCM. New collected data show that the QP nappe was affected by at least three phases of ductile deformation. The last two phases of ductile deformation (D2 and D3) are associated with extensional shear bands that record the exhumation of the QP nappe within the middle to upper crust. The D2 phase associated with the retrograde regional metamorphic foliation (chlorite-phengite assemblages) is followed by a D3 phase characterized by bi-vergent extensional shear zones with top to the NE-ENE and SW-WSW kinematics. Small scale and late high angle (45-50°) brittle extensional faults within the QP nappe with both top to the E and W kinematics document the brittle evolution of the metamorphic domes. RSCM data and P-T paths construction are used to identify the different tectono-metamorphic units within the QP nappe at a high resolution and at least 4 sub-units were identified in northern Peloponnese with Tmax varying between 350° and 580°. A network of low-angle normal faults thins the overlying nappe stack and root into the Cretan detachment at the top of the metamorphic domes. 3D structural modelling and cross-section construction around the metamorphic windows suggest that exhumation of the metamorphic domes was associated with 3D extensional thinning of the overlying nappes during the Miocene with both arc-parallel (N-S) and arc-normal extension (NE-SW). The relationship between the exhumation of the HP units and the thinning of the Hellenides as well as regional tectonic implications are discussed in this talk.

Subduction erosion associated with Paleo-Tethys closure: Insights from Early Paleozoic accretionary complexes in western Yunnan, SE Tibetan Plateau

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Keywords: Langcang Group, Paleo-Tethys, Accretionary complexes, SE Tibetan Plateau.

Accretionary complexes constitute the remnants that are derived from ocean basin disappearance and can be preserved in the subduction zone, which can then represent the final position of the ancient ocean basin subduction and disappearance (Kusky et al., 2013). The identification of accretionary complexes in orogenic zones is key to dissecting the dynamics of orogenic processes. The Changning-Menglian orogenic belt (CMOB) in the southeastern Tibetan Plateau is considered as the main suture of the Paleozoic Paleo-Tethys that separates Gondwana-derived continental fragments from Eurasia-derived ones (Sone & Metcalfe, 2008; Wang et al., 2018). However, the geological bodies that record the subduction and accretionary orogeny of the Changning-Mengliang Ocean have never been clearly identified, limiting the reconstruction of the tectonic history of Paleo-Tethys in western Yunnan. We study the material composition, geochronology and petrography of the Lancang Group in the CMOB.

According to a 1:50,000 regional geological mapping survey, the Lancang Group is dominated by schist, consisting of metamorphic volcano-sedimentary rocks. These rocks have undergone three phases of deformation and metamorphism with outcrops that are typica for an accretionary complex (block-in-matrix). Detrital zircons from the metasedimentary schists yield the youngest peak age of 450 Ma. Igneous zircons from metavolcanic samples reveal protolith ages of 474–476 Ma. Combined with previous data, our data confirm the early Paleozoic age of formation of the Lancang Group. In this Group, a series of blueschists and eclogites were recently discovered in the substrate as N-S-direction lens-shaped inclusions. The glaucophane eclogites samples in the Bangbing area show a peak assemblage of garnet + omphacite + phengite + lawsonite ± quartz + rutile, with peak P–T conditions of 30.0–32.7 kbar and 617–658°C. These eclogites samples display OIB- and E-MORB-like geochemical affinities, respectively, and have whole-rock $\varepsilon_{Nd}(t)$ values in the range of 3.18–5.45, suggesting that their protoliths were mainly oceanic crust with limited crustal assimilation.

The study shows a complex material composition of the Lancang Group, which has undergone multiple and overlapping phases of metamorphism and deformational events. The co-occurrence of multiple types of HP metamorphic rocks suggests that the CMOB represents a typical oceanic subduction-accretionary belt. The results provide important basic information for further research on the geodynamic evolution of the Paleo-Tethys.

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Reconstruction of dismembered Ocean Plate Stratigraphy (OPS) in the Blovice accretionary complex, Bohemian Massif

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Keywords: Avalonian–Cadomian belt, Blovice accretionary complex, Bohemian Massif, mélange.

Ocean Plate Stratigraphy (OPS) refers to stacked lithologies that record the travel path of an oceanic plate from the spreading center towards the subduction zone. From bottom to top, OPS typically includes a basal MORB layer, OIB (+/- carbonate caps), pelagic chert, and turbidite deposits as the main members. Although arguably the best examples of OPS were described in the circum-Pacific realm, the Cadomian, late Neoproterozoic to early Cambrian Blovice accretionary complex in the Bohemian Massif was recently recognized as hosting superbly exposed mélange examples that likely formed by mixing of subducted ocean floor and upper plate material (arc-derived siliciclastics), thus representing relicts of a disrupted OPS. This contribution describes formation of OPS in the Blovice complex, which may be summarized as follows. The oceanic plate that was consumed by Cadomian subduction was likely a relatively young back-arc basin composed of MORB, OIB, and extensive deposits of hydrothermal, pelagic and hemipelagic cherts. Minor ramps or rims of shallow-water carbonates formed around the OIB seamounts. Floor of this oceanic plate presumably exhibited a rugged topography, where high volcanic ridges or seamount chains were separated from each other by flat basins. Although some sedimentary mélanges may have already formed along the outer trench slope, the main phases of mélange formation occurred when seamounts entered in the growing accretionary wedge. Gravitational instability of the wedge front triggered mass wasting processes forming intense submarine slumping and sedimentary mélanges (olistostromes). The mechanical decapitation or disruption of both seamounts and ridges mixed dismembered blocks of MORB and OIB with the arc-derived host material forming tectonic mélanges. Following the interaction and superposition of tectonic and sedimentary (gravitational) mixing process, the basalt-bearing mélanges recorded several phases of tectonic deformation: thrusting and flattening (as determined using the anisotropy of magnetic susceptibility, AMS) and late faulting that exhumed parts of the accreted material. During faulting, the wedge was locally in extension and silicified black shales were deposited on top of the turbidites in small trench-slope basins. Finally, detrital zircon geochronology suggests that accretion and mélange formation occurred from ca. 590 Ma to ca. 527 Ma in several major pulses closely related to subduction of topographic elevations (seamount chains), separated by periods of normal seafloor deposition of coherent bedded successions.

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S6.

Rock rheology and petrophysical properties of crustal and mantle rocks

CONVENERS & CHAIRPERSONS

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Deformation mechanism and textural formation of hornblende – Insights from natural samples and laboratory experiments

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Keywords: deformation mechanism, texture, subduction zone, Horneblende, plastic deformation.

Hornblende, Ca-rich amphibole, comprises rocks in the lower mantle and forms as the product of metamorphic reactions and hydration of mafic rocks. Hornblende textural and rheological properties are highly affected by the inherent anisotropic properties of its crystals. In addition, deformation mechanism and formation of crystallographic preferred orientation (CPO) affect and affected by each other and their evolution is not well-understood. For example, unlike quartz, calcite, or olivine, CPO of hornblende does not necessarily suggest deformation via dislocation-mediated creep and was mostly interpreted to form under different mechanisms such as semi-brittle and cataclastic flow, dissolution precipitation, dislocation creep, recrystallization, micro-twinning, and diffusion assisted creep. I will present and discuss microstructural analysis of natural samples and experimentally deformed samples using electron backscatter diffraction (EBSD). Hornblende-rich metabasalts part of the Mamonia complex (Cyprus) from two localities – Bath of Aphrodite (BOA) and Aya Varvara (AV) were analyzed. Hornblende grains show strong CPO consistent with the common alignment of the [001] axis with the lineation direction. However, in the (100) and (010) directions BOA shows girdles in the plane normal to the lineation (YZ-plane) while AV shows orthorhombic structure with (100) point maxima align normal to the foliation (Z-axis). Intragrain misorientations and preferred orientation of the intragrain misorientation axis suggests that the axial texture of BOA formed during oriented grain growth and, or, rigid body rotation, while the orthorhombic symmetry of AV formed under plastic, dislocation mediated creep. Deformation experiments run under 1 GPa confining pressure allows to investigate the microstructural properties of samples deformed under a range of temperatures (under 400 and 800 °C, respectively). Experiments reveal folding and kink bands, accommodated by both plastic mechanisms, via dislocation glide on the hornblende easy slip system, and brittle mechanisms, via micro-fracturing along the crystal cleavage (110). I will further discuss our ability to interpret hornblende texture and seismic anisotropy from natural field-based tectonic regimes while assessing the possible contribution of laboratory experiments to understand the dynamic and mechanics of the lower mantle and subduction zones.

Deformed pseudotachylytes from the Silvretta basal thrust – stress-strain conditions during interseismic periods

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Keywords: pseudotachylytes, (ultra-)mylonites, postseismic creep, multiple high-stress events, brecciation

Pseudotachylytes and (ultra-)mylonites occur at the Silvretta basal thrust in the central alps, Austria. Pseudotachylytes themselves may be deformed. They can crosscut other pseudotachylytes, can be brecciated or transformed into (ultra-)mylonites. The formation of pseudotachylytes is associated with high strain-rates and high stresses (σ_d > 400 MPa) as indicated by (-101) twins in amphiboles at greenschist facies conditions. Here, we focus on the deformation conditions during deformation of the pseudotachylytes to address the questions whether the deformed pseudotachylytes reflect (i) localized strain during postseismic creep at relaxing stresses, or (ii) multiple transient high-stress events.

Pseudotachylyte-bearing quartz-rich gneisses can contain folded and foliated pseudotachylyte injection veins. Recrystallized grains with shape preferred orientation (SPO) and crystallographic preferred orientation (CPO) in the host rock adjacent and associated to the folded and foliated injection vein indicate quartz dislocation creep after pseudotachylyte formation. Ultramylonites occur, which are characterized by a fine-grained mica-rich matrix (< 5 µm) enclosing deformed quartz clasts with recrystallized quartz grains with CPO and SPO, indicating quartz dislocation creep during formation of the ultramylonite. Also, cataclastically deformed large feldspar clasts (several hundred µm) may be embedded in these ultramylonites, which are interpreted as deformed pseudotachylytes. The deformed quartz-rich host rocks with folded injection veins as well as ultramylonites indicate deformation after pseudotachylyte formation at conditions that allow dislocation creep of quartz. However, quartz-rich host rocks deformed in association with pseudotachylytes also can indicate growth of new grains from highly damaged zones at quasi-isostatic conditions, as indicated by their small size (a few µm in diameter) and isometric shape without internal misorientation and crystallographic preferred orientation. Pseudotachylyte layers concordant to the foliation of the host can be brecciated, containing rotated pseudotachylyte clasts. This indicates brecciation after cooling of the pseudotachylyte, suggesting that they represent separate events, as opposed to an interaction of simultaneous ruptures. The large variety of microstructures records localized deformation during postseismic creep at very different stress conditions that allow for quartz dislocation creep as well as localized affectation by multiple seismic events.

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Variation in rock fabric with depth in the upper 1 km of the earth's crust and its implications for mineralization – a study from the Singhbhum region (India)

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Keywords: rock fabric, mineralization, AMS, Micro-CT, SEM-EBSD.

Mineral deposits are commonly associated with shear zones and hydrothermal veins in the upper 1 km of the earth's crust. Hence, any study that enhances our understanding of the variation in fabric, porosity and permeability with depth can provide useful information to better appreciate structural control on vein formation and mineralization. In the present study we have carried out analysis of rock fabric, its anisotropy, as well as porosity and permeability studies in metapelitic rocks from the vicinity of the Singhbhum Shear Zone (eastern India). Copper, and uranium mineralization is known from this region, and our study was carried out on 10 drilled cores of schists taken from various depths viz. 112 meters to 850 meters. We applied various techniques to analyze physical properties and identify the fabric in the samples from different depths viz. (a) ultrasonic P-wave velocity (Vp) measurements (b) X-ray micro-CT followed by porosity and permeability calculations (c) anisotropy of magnetic susceptibility (AMS) measurements followed by petrofabric quantification and (d) SEM-EBSD studies of rock thin sections. Data obtained upto now allow us to better understand the relation between rock anisotropy, porosity and permeability with depth, and the influence of these parameters on the formation of veins. We observe that (a) Vp in the borehole samples ranges between 5000 - 4000m/s. However, it falls sharply to 2297m/s in depths between 405m – 588 m. (b) The magnetic anisotropy from AMS studies, which is a gauge of the intensity of the fabric (Pj) ranges between 1.163 to 1.811. The high values between 1.5-1.8 are recorded in samples between 405m-758m depth, while a sharp fall to 1.19 is noted in sample from 547m depth. (c) Micro-CT data reveals the sample from shallow depth (112m) has minimum porosity, while high porosities (>5%) are recorded in samples from 405m and 547m depths. (d) Largest and smallest pore sizes are recorded, respectively, at 405m depth and 547m depths. (e) Sample from 547m depth has a high permeability of 157 x 10^4 Darcys followed by the sample from 850m depth with permeability of 134 x 10^4 Darcys; other samples have lower permeability. (f) Although, quantification of shape preferred orientation (SPO) defined by phyllosilicates in samples from varying depths is in progress, quartz CPO from SEM-EBSD data reveals the dominant slip system to be basal <a>, which is expected in these low-medium grade metamorphosed schists. These results are interpreted in the context of the microstructures. Compositional layering and thick bundles of chlorite and mica are observed in samples from depths between 405m and 588m. This along with increase in pore spaces in the samples may be responsible for a drop in Vp at these depths. Our data reveal a negative correlation between Vp and porosity. Further, the sample from 547m depth, is replete with veins and we infer that reduction in pore size is due to fluid flow and (re)crystallization in the pores. Since, the mineralization in the Singhbhum region (India) is reported from hydrothermal veins, we envisage that the approach adopted in our study can enhance knowledge of the relation between fabric anisotropy, porosity, permeability, vein occurrence and depth. This has implications to better understand the control of the above properties on mineralization and hence on mineral exploration as well as planning.

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Frictional-viscous cycles in the Brossasco-Isasca Unit (Dora Maira Massif, Western Alps) metagranitoids: from field mapping to microstructures

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Keywords: pseudotachylyte, mylonite, frictional-viscous cycles, Brossasco-Isasca Unit, Dora Maira Massif.

In this contribution the relationships between mylonite, cataclasite and pseudotachylyte, hosted in the in the Brossasco-Isasca Unit (Cosca et al., 2005), in the south-western portion of the Dora Maira Massif (Western Alps) have been analyzed. A multi-scale structural geology approach, starting with the compilation of a detailed geological-structural map of the area, highlighted the occurrence of a deformation gradient into metagranitoids. Emphasis was given on the observations of overprinting relationships, of the different types of "fault" rocks, in the field, followed by their microstructural characterization on thin sections of selected samples. The structural evolution of the area (Henry et al., 1993), from the greenschist facies metamorphic re-equilibration associated to non-coaxial ductile shearing, up to the latest brittle structures was reconstructed. Different types of mylonites, developed under general flow conditions determined through the study of kinematic vorticity (Kurz & Northrup, 2008), with a top-to-the SW/W sense of shear during greenschist facies metamorphism have been recognized and mapped. Pseudotachylyte and cataclasite, hosted in the mylonitic gneiss (Cosca et al., 2005; Zechmeister et al., 2007), nucleated often on structural discontinuities such as the mylonitic foliation or compositional banding (Sibson, 1980). Interesting overprinting relationships between fault rocks, pseudotachylyte veins and foliated/mylonitic pseudotachylyte are described (Zechmeister et al., 2007). These relationships were tentatively linked to different frictional-viscous cycles (Handy & Brun, 2004) in which at least two generations of pseudotachylyte have been distinguished. The microstructural study allowed to infer useful information on the kinematics of the fault rocks, on their overprinting features and on the possible temperature range of mylonite and pseudotachylyte formation (Bestmann et al., 2011).

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Role of amphibole fabric formation and the rheology of subduction shear zones, two examples from exhumed blueschists in the Ryukyu arc (SW Japan) and Lento Unit (Corsica, France)

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Keywords: Amphibole rheology.

In subduction zones, ocean-derived mafics are, along with sediments, the main lithologies involved in deformation along the plate interface. In particular, blueschist rocks represent the remnants of oceanic crust that is subducted at high pressure-low temperature metamorphic conditions. In deformed metabasites, amphiboles are abundant foliation forming minerals at the blueschist-greenschist-amphibolite conditions that prevail at the base of the subduction thrust seismogenic zone. As such, amphiboles are likely an important control on subduction interface rheology, but the mechanisms that govern their deformation are still debated.

In fact, there is not extensive detailed knowledge on how blueschist rocks deform, however investigating the foliation forming minerals such amphiboles can shed light on it, as blueschist foliation represents the product of subduction deformation processes and is therefore likely to control rheology.

We present and compare data from an exhumed subduction complex in the Ryukyu arc, in the SW Japan, where Triassic blueschist facies metabasites outcrop in block in matrix structure. We compare these with the meta-ophiolites of the Lento Unit in the Alpine Corsica, where blueschist facies metabasites of Middle to Late Jurassic age are embedded in a calcschist matrix. The comparable structural asset and mineralogical assemblage of these two blueschist complexes offers an important natural laboratory where to study amphibole foliation development in ocean-derived HP-LT rocks.

Through multiscale and multidisciplinary studies, field- and laboratory-based, we aim to understand amphibole rheology by analysing deformation characteristics of blueschist rocks from different geodynamic environments. Firstly, by documenting the deformation mechanisms active in blueschist rocks through electron backscatter diffraction (EBSD), with the quantification of intracrystalline deformation and of lattice preferred orientation (LPO) development. Secondly, by quantifying fabric development through grain size and mineral shape analysis, in order to understand the role fabric has in foliation development. With our studies, we hope to implement the growing database on the effect of amphibole deformation in the rheology of mafic rocks.

High-strain deformation of ice Ih

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Keywords: anisotropy, crystallographic preferred orientation, microstructure modelling, high-strain deformation.

Polar ice sheets contain deformation structures identical to those found in ductile rocks, such as folds and high-strain zones. Polycrystalline ice deforms by dislocation glide, preferentially along the basal plane, which has a slip resistance that is at least 60 times lower than that for other slip planes. The preferred glide on basal planes leads to a crystallographic preferred orientation (CPO) that makes the ice highly anisotropic. To identify deformation structures, the visual stratigraphy of polar ice is essential, as ice otherwise has no strain markers. Surface velocity data from the Greenland Ice Sheet shows a highly heterogeneous deformation behavior. Understanding the flow behavior of ice is of major importance, as discharges from the Greenland Ice Sheet has been the main control factor for sea level rise in recent years. Here we investigate the influence of an initial single maximum CPO on the deformation behavior of ice Ih, using the VPFFT crystal plasticity code (Lebensohn and Rollett, 2020) coupled with ELLE (www.elle.ws; Piazolo et al., 2019). We deform the intrinsically anisotropic ice Ih in dextral simple shear up to a shear strain of $\gamma = 30$ and systematically varying the orientation of the initial CPO. We analyze the evolving deformation structures in systems with the shear plane parallel (horizontal) and also slightly tilted layers representing the stratigraphy of polar ice. For low strain the orientation of the CPO controls the deformation style. Evolving structures range from relatively stable shear plane-parallel synthetic shear zones, rotating antithetic shear bands to distributed deformation, and transitional regimes. However, at the latest at $\gamma = 30$ in almost all cases the material is strongly mixed and the initial CPO gets overprinted, in some cases already after $\gamma = 5$. Small changes in the layer inclination lead to variable deformation structures, such as synthetic shear bands that are visible after a small amount of strain when layers are inclined. With some CPOs the rotation of basal planes towards being parallel to the shear plane is much faster than in other cases. Basal planes in high strain rate zones almost always rotate faster in comparison to those in lower strain rate zones. The stress evolution shows both hardening and softening stages depending on the initial CPO, but the system reaches a steady-state after $\gamma = 5$, much faster than the overprinting of the initial CPO.

Our results highlight the challenge to identify and interpret deformation structures in large ice masses. The highly anisotropic properties of ice Ih lead to localized and scale-independent deformation (de Riese et. al., 2019), and dynamical processes operating on the micro scale may also operate on the meso- and macro-scale.

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Permeability evolution of Bentheim sandstone at georeservoir conditions

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Keywords: Petrophisycs.

Because of its petrophysical properties Bentheim sandstone is regarded as a reference rock material in laboratory experiments of rock mechanics: it is quasi monocrystalline (quartz up to 97%), with a well-sorted grain size distribution and well-connected pores, showing lateral continuity and homogeneous geometric, hydraulic and mechanical properties at the block scale. In addition, this rock has a high porosity and high permeability (around 25% and 1000 mD, respectively), and a low hygric expansion as clay minerals constitute only minor components of the mineralogical assembly.

Unsurprisingly, Bentheim sandstone, as a georeservoir, has been extensively tested in triaxial conditions for a variety of purposes, from oil and gas exploitation to geothermal energy and carbon storage and sequestration projects. Furthermore, Bentheim sandstone has been used as a building stone, particularly in the Netherlands, since the 11th century. Therefore, it is important to fully understand its behaviour at different pressure, temperature and hydraulic conditions.

Previous laboratory studies have shown how the permeability of Bentheim sandstone is affected by effective confining pressure, bedding orientations and axial strain. In particular, it has been observed that an increase in effective pressure, corresponding to an increase in depth, does not influence the permeability of this sandstone. In reservoir geomechanics, this is a crucial finding. However, rocks at depths also experience different temperature and fluid pressure conditions, as well as different types of historic stress evolution. Although, general relationships between permeability and these parameters do exist, their specific effect on Bentheim sandstone has never been investigated in detail.

Based on triaxial experiments in a state-of-the-art apparatus, we demonstrate on large (250 x 100 mm) cylindrical samples the behaviour of Bentheim sandstone for quasi reservoir conditions. Our goal is to fill in the gap in understanding the hydromechanical behaviour of this rock and concomitant permeability changes at different georeservoir conditions, where a suite of geomechanical parameters is investigated.

Seismic fracturing under high grade conditions in a subduction zone (Central Cordillera, Colombia)

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Keywords: paleo-seismicity, ophiolites, geothermobarometry, fractures.

Multiple slivers of oceanic crust are exposed along the Romeral fault, located in the central Cordillera in Colombia. Gabbroic samples show multiple generations of shear and tensile fractures and subsequent static recrystallization of a garnet and clinopyroxene assemblage. Clinopyroxene grew as coronas around garnet, consuming plagioclase, but this metamorphic event was incomplete, and the rocks still contain large amounts of disequilibrium plagioclase. This is possibly due to the lack of either ductile deformation or substantial water influx during or after fracturing. It seems that the tensile fractures developed without significant pore fluid pressure, which is only possible due to extremely high differential stresses. We hypothesize these were achieved during a seismic event in lower crustal levels.

The transformation of the rocks was not only extremely limited under high grade conditions, but they also appear to have evaded any further retrogression during exhumation and activity of the strike-slip Romeral fault. We are confident that compositions of the statically recrystallized mineral assemblage will reflect the close to peak metamorphic conditions, and thus thermobarometry will compliment past studies, which were somewhat indifferent about whether the ophiolitic slivers experienced metamorphism in a subduction channel or during simple accretion.

Elastic anisotropies of deformed upper crustal rocks in the Alps

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Keywords: CPO.

The crust within collisional orogens is very heterogeneous both in composition and grade of deformation, leading to highly variable physical properties at small scales. This causes difficulties for seismic investigations of tectonic structures at depth since the diverse and partially strong upper crustal anisotropy might overprint the signal of deeper anisotropic structures in the mantle. We characterized the range of elastic anisotropies of deformed crustal rocks in the Alps according to the crystallographic preferred orientation (CPO) of their constituent mineral phases. Furthermore, we modelled average elastic anisotropies of these rocks and their changes with increasing depth due to the closure of microcracks. For that, pre-Alpine upper crustal rocks of the Adula Nappe in the central Alps, which were intensely deformed during the Alpine orogeny, were sampled. The two major rock types found are orthogneisses and paragneisses; however, small lenses of metabasites and marbles also occur. CPOs and volume fractions of minerals in the samples were measured using time-of-flight neutron diffraction. Combined with single crystal elastic anisotropies these were used to model seismic properties of the rocks. The sample set shows a wide range of different seismic velocity patterns even within the same lithology, due to the microstructural heterogeneity of the deformed crustal rocks. To approximate an average for these crustal units, we picked common CPO types of rock forming minerals within gneiss samples representing the most common lithology. These data were used to determine an average elastic anisotropy of a typical crustal rock within the Alps. Average mineral volume percentages within the gneiss samples were used for the calculation. In addition, ultrasonic anisotropy measurements of the samples at increasing confining pressures were performed. These measurements as well as the microcrack patterns determined in thin sections were used to model the closure of microcracks in the average sample at increasing depth. Microcracks are closed at approximately 740 MPa yielding average elastic anisotropies of 4 % for the average gneiss. This value is an approximation, which can be used for seismic models at a lithospheric scale. At a crustal or smaller scale, however, local variations in lithology and deformation as displayed by the range of elastic anisotropies within the sample set need to be considered. In addition, larger-scale structural anisotropies such as layering, intrusions and brittle faults have to be included in any crustal-scale seismic model.

Microstructures superposition in marble mylonites: a tool to infer the progressive deformation of the South Tibetan Detachment System in Himalaya

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Keywords: Calcite fabric, differential stress, twinning, rheology, Himalaya.

The low competence contrast between rheological domains in homogeneous marble mylonite makes it difficult to distinguish, at a first glance, those kinematic indicators typically used to characterize a shear zone. Nevertheless, the observation of calcite microstructures is promising in understanding the deformation regime at a small scale, to infer more regional information (Molli &Heilbronner, 1999; Spanos et al., 2015; Negrini et al., 2018). In this contribution, we focus on calcite microstructures and their superimposition to constrain the deformation style of a regional-scale shear zone, the South Tibetan Detachment System (STDS) in the Manaslu area of central Himalaya (Western Nepal). Here, carbonate rocks are the main lithotypes cropping out within over 1 km-thick mylonitic zone, where a top-down-to-the-north sense of shear is mainly defined by asymmetric folds, rare asymmetric porphyroclasts, and oblique foliations. We combined calcite grain size, twins, crystallographic preferred orientations (CPOs) data, and petrographic observations to define the contribution and timing of two main deformation mechanisms in calcite: grain boundary mobility and twinning. Calcite CPOs highlighted that both mechanisms were active during the STDS shearing. By comparing deformation temperature, differential stress, strain rates, and kinematic vorticity results, we defined different deformation conditions at which grain boundary mobility and twinning were dominating on each other, testifying to a progressive shallowing of the detachment. Ductile deformation evolved from deeper to shallow crustal levels, where decreasing temperatures and increasing differential stress produced strain hardening still under ductile regime. This contribution highlights how marble rheology influenced, on a regional scale, the exhumations along a low-angle shear zone from the middle to the upper crust.

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Influence of H_2O on deformation behavior and microstructure of quartz: deformation experiments on Tana-quartzite

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Keywords: quartz, deformation experiments, H_2O, recrystallization, microstructures.

Quartz is among the most abundant minerals in the continental crust and one of the first to show plasticity with increasing pressure and temperature. Understanding its mechanical behavior is crucial for estimates on crustal strength and geodynamic modeling. Since the discovery of H_2O-induced weakening of quartz, a remarkable amount of work has been done in order to improve the understanding of processes and mechanisms controlling the phenomenon. As the weakening effect depends on molecular H_2O, it is a disequilibrium process that is difficult to incorporate into the existing quartz flow laws. We performed a series of coaxial deformation experiments in the solid-medium Griggs-type apparatus, using natural Tana-quartzite (northern Norway). Samples with added H_2O in the range of 0-0.5 wt% were deformed at conditions of 900 °C and 1 GPa, in 1) shortening experiments with constant strain rate of 10^{-6} s^{-1} and 2) strain rate stepping experiments covering 10^{-5}, 10^{-6} and 10^{-7} s^{-1}. Compared to the as-is samples, samples with the lower amounts of added H_2O (0.1 to 0.2 wt%) show slightly weaker mechanical behavior. On the other hand, samples with higher amounts of added H_2O (0.3 to 0.5 wt%) show more erratic and less systematic behavior. The strain rate steeping experiments show surprisingly low stress exponent values of ~2. The most deformed regions in the weaker samples are in the vicinity of thermocouple, characterized by intense flattening of the original grains and limited recrystallization associated with subgrain rotation and cracking. With addition of H_2O, abundance of SGR-related domains decreases, while the cracking-related recrystallization becomes more dominant. Cracked domains are associated with fluid/melt pockets, where the cracked fragments underwent subsequent grain growth. The grain growth or reconstitution of quartz by grain boundary migration is best visible in CL-images, where such material shows blue luminescence. FTIR spectroscopy documents that the original grains during deformation lose H_2O manifested by decrease in H_2O concentration from 600-2000 H/10^6 Si to 0-400 H/10^6 Si. In contrast, the average H_2O concentration present in grain boundaries is increasing with increases in amount of added H_2O. Intense flattening of the original grains accommodated by dislocation creep is associated with loss of H_2O from the grains interior. Recrystallized grains nucleated by cracking and subgrain rotation indicate concurrent operation of brittle and crystal plastic processes. The documented presence of H_2O along grain boundaries in the recrystallized domains facilitates reconstitution of quartz through grain boundary migration and dissolution-precipitation processes. The low stress exponent and observed microstructural features suggest that bulk strain is mainly accommodated by dissolution-precipitation combined with grain boundary sliding. Increased amount of H_2O in grain boundaries with higher quantity of added H_2O promotes crack-related recrystallization, which however does not significantly affect the strength of the samples.

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Slip velocity and fault stability in serpentine-rich experimental faults

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Keywords: friction, serpentinite, velocity dependence, faults, rock mechanics.

The rate and state framework is widely used to study and quantify fault stability through the analysis of the frictional properties of fault rocks. Fundamental parameters are individuated in the *a-b* value, the critical slip distance D_c, and the critical stiffness k_c, which is derived by their combination. These parameters are known not to be constant even when the same fault material is tested, but to depend on the chosen experimental conditions. Special interest is dedicated to the effect of sliding velocity on the rate and state parameters (e.g., Im et al., 2022 and references therein), but no clear physical nor qualitative constraint has been proposed so far. We explored this problematic by performing friction experiments on Elban serpentinite (composed mainly by lizardite and magnetite) powders, which show strong variation of frictional properties with sliding velocity.

Serpentinite powders (< 125 µm grain size) were sheared at four different normal stresses (25, 50, 75 and 100 MPa) in the biaxial apparatus BRAVA. The experiments consist of an initial phase of sliding at 10 µm/s, a slide-hold-slide test, and two series of velocity stepping (sliding velocity incremented discretely from 0.1 to 300 µm/s). The material shows friction of ~0.4 with velocity weakening behaviour and negative frictional healing. The module of the negative a-b parameter increases neatly with decreasing sliding velocity while Dc decreases (from 7 to 2 µm), causing k_c to rise. At low velocities (< 3 µm/s) sliding is unstable and the fault undergoes stick-slip behaviour. This is explained by the increase of the critical stiffness to values higher than the loading system stiffness.

Back-scattered SEM images of the principal slip zones of recovered samples show a lizardite-rich foliated shear zone dispersed with rounded magnetite porphyroclasts. We interpret the variation of frictional properties with the relative interaction of the strong and stiff magnetite grains, which, at low sliding velocities, interact creating force chains and promoting unstable slip. At higher velocities, dilation and separation of the porphyroclasts promote the activity of c-planes within the weaker phyllosilicates (lizardite) thus favouring stable slip.

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Panta rhei…But how? Deformation mechanisms at the eclogite type locality (Saualpe-Koralpe Complex, Eastern Alps, Austria)

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Keywords: eclogite deformation, microfabric, dislocation creep, diffusion creep.

The presence of large volumes of eclogite in collision and subduction zones makes their formation and deformation highly relevant for the dynamics of convergent zones. There is however no consensus on the deformation behavior of eclogite. On the one hand, mylonitic eclogite shear zones showing evidence of dominant deformation by dislocation creep have frequently been reported. On the other hand, fluid supported formation and deformation has been recently suggested as a potential mechanism in eclogite whereby the main accommodating mechanism is dissolution-precipitation creep. This raises the question of the factors controlling the deformation behavior of eclogite.

In this contribution, we present microstructural, petrographical and chemical data from a series of eclogite samples derived from low Mg – high Ti gabbro collected at the eclogite type locality (Saualpe- Koralpe Complex, Eastern Alps, Austria). The rocks are characterized by a pronounced foliation defined by the shape preferred orientation of the major minerals (omphacite, amphibole, epidote and garnet). Minor euhedral quartz grains are present. Overall, grains show rather uniform extinction which is well in line with a low internal distortion detected by electron backscatter diffraction mapping. These features are interpreted as evidence of syn-tectonic diffusion dominated eclogitization. Thermodynamic forward modelling indicates that eclogitization occurred under fluid saturated conditions at around 2 GPa and 640–680°C. Locally, the eclogite fabric is crosscut by finite veins showing a similar paragenesis as the host eclogite. However, they are enriched in quartz and epidote, depleted in garnet and show overall a coarser grain size. These veins likely initiated as post-eclogitization fractures that were subsequently filled by eclogite facies minerals. Depending on their initial orientation, the veins were either reactivated as flanking structures or foliation sub-parallel shear zones. The reactivated veins are characterized by undulatory extinction, twinning and subgrain formation, all being indicative of dislocation creep. The identical paragenesis and similar mineral chemistry indicates that reactivation occurred at conditions close to those of eclogitization. The investigated samples therefore testify that eclogite can deform by different deformation mechanisms at similar conditions. Our investigations document that diffusion (and/or dissolution-precipitation) is bound to the process of eclogitization, eclogite facies vein formation is accommodated by fracturing and dissolution-precipitation whereas post-eclogitization strain localization is accommodated by dislocation creep.

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Deformation, reactions and phase mixing in the upper mantle shear zone of northwestern Ronda (Spain)

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Keywords: shear zone, upper mantle, phase mixing, microstructure, strain localization.

On the northwestern boundary of the world's largest exposure of subcontinental mantle a major shear zone crops out. Showing common characteristics of upper mantle shear zones like an increase of (re)crystallized grains and an overall decrease in grain size towards the shear zone front, ultramylonites are not present. Reaction induced phase mixing has been shown to be crucial for the formation of ultramylonitic assemblages in other upper mantle shear zones (Lanzo, Othris, Erro Tobbio). By the microstructural analysis on a transect from the shear zone front to 703 m distance, our research investigates the extent and the origin of phase mixing in the Ronda shear zone and evaluates its impact on strain localization.

Pyroxenes and spinel were found as interstitial or film-like grains in the either thoroughly mixed or olivine dominated matrix. Olivine has a strong, common crystallographic preferred orientation (CPO). Beside phase mixing in the matrix, polyphase neoblast tails formed on the expanse of pyroxene porphyroclasts. In the tails the olivine CPOs are weaker which could indicate the presence of fluids. Both microstructures, mixed matrix and porphyroclast tails indicate a two-step process of phase mixing in the Ronda shear zone. (1) The first step is represented by the interstitial and mostly internal deformation-free pyroxenes and spinels, found independent of the distance to the shear zone front, in the matrix. Their small grain size, irregular film-like shape and sinuous, xenomorph grain boundaries point to a crystallization from interstitial Si-rich melts. These melts have their origin within the deeper part of the peridotite complex and are associated to a thermal event after thinning of the subcontinental lithosphere (Soustelle et al., 2009). (2) The second step is evidenced by an increasing amount of pyroxene porphyroclast reaction tails towards the shear zone front. The tails consist of pyroxene, amphibole, olivine ± spinel neoblasts which partly indent into the parent pyroxene clast. The presence of amphibole in these tails and their increasing occurrence towards the shear zone front indicate a fluid infiltration from the shear zone front.

Both aforementioned processes demonstrate that phase mixing in the northern Ronda shear zone was reaction induced. Even though reactions led to the disintegration of pyroxene porphyroclasts into polymineralic tails, the strain was not localized there, and no ultramylonite bands were formed. The absence of strain localization in these tails is likely due to the lack of a switch from dislocation creep to diffusion creep. Together with the presence of an overall strong olivine CPO it indicates a broad distribution of deformation in the mixed matrix over the entire shear zone width, accommodated by dislocation creep.

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Long-term creep and transient high-stress deformation in shear zones

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Keywords: shear zone, high stress-loading rate, transient deformation, long-term creep, crack-seal.

Long-lived activity of large shear zones offsetting crustal blocks over tens of kilometres is governed by episodes of transient deformation caused by coseismic loading (within seconds to minutes) and creep during postseismic relaxation (within tens to thousands of years) at the critical depth just below the seismogenic zone, i.e. at greenschist facies conditions. Shear zone rocks exhumed from these depths provide unique information on the deformation conditions. Pyroxene and amphibole twins indicate characteristic transient stresses for coseismic deformation to be on the order of several hundred MPa. The times scale of loading to these stresses corresponds to the seismic slip event in the overlying seismogenic layer, i.e. on the time scale of seconds-minutes. Other minerals respond to these high stress-loading rates by instantaneous, distributed fracturing, as for example quartz and garnet, indicated for example by quartz C'-type shear band foliations and bookshelf-structures of garnet, respectively. Overall strain during the stage of coseismic deformation is relatively low due to the transient nature of the stress-strain conditions. Yet, the stored strain energy influences subsequent deformation at relaxing stresses during the interseismic periods. During these interseismic periods, strain rates can be on the order of 10^{-10} s^{-1} to 10^{-9} s^{-1} at lower stress conditions of a few tens of MPa. This high strain – low stress deformation is showing characteristically different microstructures with evidence of dissolution precipitation creep and vein formation with crack-seal microstructures. Such cyclic deformation at high stress – low strain conditions, triggered by coseismic loading and subsequent deformation at high strain – low stress conditions within interseismic periods are prerequisite for large-scale movement of crustal blocks, as for example the exhumation of high-pressure-low temperature metamorphic rocks from Crete.

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Multiscale analysis of physical rock properties at Stromboli Volcano: what controls the frictional properties?

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Keywords: Volcanoes Collapse, satellite observation, rock properties, multiscale fracture density, friction.

Stromboli volcano, located in the north-easternmost island of the Aeolian archipelago (Southern Italy) and well known for its persistent volcanic activity, has experienced at least four sector collapses over the past 13 thousand years. The most recent activity resulted in the formation of the Sciara del Fuoco (SDF) horseshoe-shaped depression and a tectonic strain field believed to have promoted flank collapses and formed a NE / SW trending weakness zone across the SDF and the western sector of the island (Tibaldi, 2001). The tectonic strain field interplayed with dyking and fracturing appears to control the episodes of instability and the onset of slip surfaces. This study presents new data identifying areas of damage that could promote fracturing via remote sensing and rock friction measurements taken on rocks around the SDF and the coupled "weak" zone. We have carried out a multiscale approach by integrating satellite observations with block and sample scale physical and mechanical properties and frictional tests carried out in triaxial configuration on cm scale slabs. Over 5000 individual fractures have been at first processed through the MatLab toolbox FracPaQ to determine fracture density, slip and dilatancy tendency around the collapse scarp with results showing that dilation and slip 0.6< is more common the northern side of the SDF as well as around areas of eruptive activity (Alcock et al., 2021).

Key units have been sampled on the field (Paleostromboli, Vancori and Neostromboli) with reference to SDF and the weak zone. Physical and mechanical properties defined using elastic wave velocities, electrical resistivity, uniaxial compressive strength and elastic moduli have been assessed and inverted for comparison to field scale geophysical investigations. Finally, direct-shear tests in triaxial configuration were carried out to explore the frictional properties using rectangular basalt slabs at 5–15 MPa confining pressure in dry and saturated conditions. Preliminary results show a variation in the friction coefficient (μ) with a general μ decrease with increasing confining pressure and saturation. The most porous Neostromboli units show the lowest friction. This suggests that the textural and pre-existing crack damage variability due to the complex and different magmatic history and cooling rates do control the evolution of the frictional properties and evolving fracturing processes. Further work will structurally quantify the slip evolution throughout post-mortem microstructural observation in order to interpret the relations to the field scale weakness zone and the SDF.

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Reconstruction of the deformation environment of Shajigami shear zone at eastern margin of Abukuma Mountain, Northeastern Japan

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Keywords: calcite mylonite, shear zone, Raman spectroscopy, crustal strength, geothermal gradient.

Understanding the deformation environment of the shear zone leads to an understanding of the crustal stress and heterogeneous strain concentration in the crust. In the middle to lower crust, where rocks behave plastically, deformation conditions can be estimated from plastically deformed rocks (e.g., mylonite). However, even if the deformation temperature and differential stress are known, it is difficult to estimate the complete deformation environment including depth due to the variety of geothermal gradient. In this study, we estimated the temperature and differential stress during deformation from calcite mylonite in the shear zone, an extremely rare example where calcite mylonite and granitic cataclasite coexist. These deformed rocks are distributed along the Shajigami shear zone, which was active as strike-slip shear zone at the eastern margin of Eurasian continent during the middle Cretaceous (Hisada & Takagi, 1992). The deformation temperature was estimated by microstructures of calcite mylonite and Raman spectroscopic thermometry of carbonaceous materials (Kouketsu et al., 2014) to be the range of 220-300°C. The deformation temperatures suggest that the calcite mylonite and granitic cataclasite were deformed under the same conditions (e.g., Passchier & Trouw, 2005). The differential stress during deformation of calcite mylonite is estimated to be 35-80 MPa by grain size piezometer of calcite (Platt & De Bresser, 2017). Given that the calcite mylonite and granitic cataclasite were deformed simultaneously, we infer that the brittle deformation for the granitic cataclasite also occurred under the differential stress. Based on these results, the differential stress of 80 MPa and deformation temperature 220˚C are considered the upper limit of the deformation environment. Assuming that the brittle deformation of the granite occurs under these conditions, we further explore the depth at deformation. Since the deformation pervasively occurred in the cataclasite, we assume the coefficient of friction due to brittle failure of intact granitic rock of 0.6 (Stetsky et al., 1974), and the pore pressure ratio of $\lambda = 0.38$. Based on these, the shallowest depth at which fracture and plastic flow simultaneously occur was estimated to be 4.7 km. Furthermore, this estimate for the depth and deformation temperature provides a geothermal gradient of 42.2°C/km. From these reconstructed deformation environments, we will discuss the rheological and microstructural properties of crustal rocks under high thermal gradient related to igneous activity at the continental margin.

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Anisotropy of magnetic susceptibility as a tool for understanding deformation of salt – example of a structural record in Kuh-e-Namak (Dashti) salt diapir

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Keywords: rock salt, rheology, salt glacier, magnetic fabrics.

The salt flow related deformation structures were studied in uniquely exposed salt body in Iran, the Kuh-e-Namak (Dashti) diapir, located ca. 100 km SE from the Bushehr city. Continuous outcrops reveal a downslope strain gradient from the domal salt in the apical part of the diapir along the glacier. Anisotropy of magnetic susceptibility was employed to address the geometry of salt flow and deformation intensity, since mineral stretching lineation and flow fabrics in halite is difficult or impossible to measure in the field. Magnetic susceptibilities range from -10×10−6 to 200×10−6 SI and are generated primarily by hematite and paramagnetic impurities in rock salt (~1-12 vol.%), formed e.g. by anhydrite, quartz, microcline and phyllosilicates. Microstructural analysis revealed that the magnetic fabric symmetry and orientation is reflected by alignment of impurities in rock salt, which are parallel to the fabric of recrystallized halite grains. The AMS exhibits three main types of fabric symmetry from clustered all directions (K1, K2, K3, orthogonal fabric) to clustered K1 directions with girdle forming K2, K3 axes and clustered K3 directions with girdle of K1 and K2 directions.

The dome of the diapir is dominated by alternating domains marked steep salt layering or NE-SW trending recumbent folds of colorful layered salt – in contrast, magnetic fabrics are regularly subhorizontal in this domain and show orthogonal symmetry of K3 cluster type fabrics. In the upper portions of the northern glacier, the salt layering is dipping south at shallow angles and is crosscut by flat shear zones that are compatible with flow of salt to the north. Further NE, on steep flanks of the dome, the macroscopic layering and the magnetic fabrics show similar pattern, marked by an ENE-WSW stretched girdle of foliation poles compatible with collapse folds transposing the originally vertical, NNW-SSE trending planes. Zone of fold axial cleavage in the middle part of the glacier reflects transposition of the steep fabrics into new flow foliation, dipping SW at moderate angles. In contrast, magnetic record in this domain shows two subfabrics, one that is compatible with the macroscopic layering and the second parallel with alignment of halite grains. Sheath folds developed in the flat plateau in the frontal part of the northern glacier, where magnetic fabrics are flat – parallel with the salt layering, but some subfabrics are steep and strike along glacier's long axis.

S7.

Interplay between tectonics, crustal melting and granitoid magmatism

CONVENERS & CHAIRPERSONS

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The Porto Belo Complex orthogneisses and granitoids as markers of collisional and post-collisional transpressive settings in the northern segment of the Dom Feliciano Belt, southern Brazil

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Keywords: Dom Feliciano Belt, transpression, oblique collision, coaxial folding, Post-collisional setting.

The Dom Feliciano Belt (DFB) extends from southern Brazil to Uruguay and is part of the Neoproterozoic Kaoko-Dom Feliciano-Gariep Orogenic System formed during the amalgamation of Gondwana. In this orogenic belt, magmatic and metamorphic events are recorded in distinct settings. The metamorphic peak is related to the main collision at ca. 660 - 650 Ma and succeeded by transpressive deformation (ca. 640 - 625 Ma) and final transcurrence (ca. 605 to 580 Ma). The space-time record of this deformation is observed in the development of dip-slip tectonics with top-to-the-NW thrusts and strike-slip tectonics along deep-seated shear zones responsible for the ascent and emplacement of magmas during the post-collisional period (ca. 640 - 580 Ma). In the northern segment of the Dom Feliciano Belt, where this work was carried out, the collisional record with top-to-NNW transport is found in the Porto Belo Complex (PBC) orthogneisses exposed as roof-pendants on the early-formed granitoids of this complex. The post-collisional period is marked by early magmatism along gently-dipping structures that evolve onto voluminous granitic magmatism synchronous to the dextral transcurrent movement of the NE- striking Major Gercino Shear Zone (MGSZ). The PBC comprises tonalitic and dioritic orthogneisses and early post-collisional granodioritic magmatism. The orthogneisses record at least one metamorphic event of yet undetermined age under amphibolite facies conditions, with the generation of a sub-horizontal gneissic banding that is folded and locally transposed during transcurrence. Despite the tectonic and magmatic activity of the MGSZ, it is possible to investigate and reconstruct the geometry of several structures of this complex, where at least three phases of folding are recognized. The first one is found only in the orthogneisses and produced recumbent isoclinal folds with NE-SW axes related to thrusting. LA-ICP-MS geochronological data indicate protolith crystallization age at ca. 805 Ma. The PBC granodiorites intrude the orthogneisses along their sub-horizontal banding, but their magmatic foliation is progressively shifted from gently to steeply dipping, and their final geometry defines the second phase of folding as asymmetrical inclined horizontal folds with a NE-SW axis and development of a mylonitic foliation concordant with the MGSZ structure. LA-ICP-MS geochronological data indicate crystallization age at *ca.* 634Ma. The third folding phase results in the development of asymmetric crenulations of NE-trending sub-horizontal axes in both rock types. The coaxial character of all three folding phases corroborates the interpretation of their nature as progressive. The simultaneous non-coaxial component is expressed mainly as the dextral mylonitic structures related to MGSZ. The coexistence of gently and steeply dipping structures during the emplacement of granitic magmas marks the transition from late collisional to the beginning of the post-collisional stage at *ca.* 634 Ma, i.e. ca. 20 Ma earlier than previously reported for the northern segment of the Dom Feliciano Belt.

Microstructural and chemical analysis of biotite- gneiss from the Boulder Creek batholith (Front Range, Colorado, USA)

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Keywords: Precambrian geology, partial melting, Proterozoic granodiorite, microstructural analysis.

The Boulder Creek batholith is a Paleoproterozoic intrusion within the Front Range in Colorado (USA) made by two suites: (i) the Boulder Creek granodiorite (1714±5 Ma; Premo & Fanning, 2000) and (ii) the Twin Spruce Quartz Monzonite (ca. 1700 Ma; Gable, 1980). The emplacement of this batholith is syntectonic with respect to the regional deformation of the surrounding metamorphic rocks. The Boulder Creek rocks probably originated from partial melting of the upper mantle and lower continental crust (Gable, 1980; Mahan et al., 2013). This contribution provides a detailed microstructural analysis of a biotite-gneiss occurring within the Boulder Creek granodiorite. New field observations suggest these gneisses are an older unit with evidence for multiple episodes of foliation development (i.e., a main penetrative foliation and a subsequent crenulation cleavage), contrasting the field relationships reported by previous mapping, in which the Bt-gneiss are instead part of a shear zone affecting Boulder Creek granodiorite (Wells, 1967). These rocks show the presence of microstructures typical of partial melting processes (i.e., melt films between grain boundaries, undeformed twinned plagioclase and peritectic cordierite). In detail, two main tectono-metamorphic stages are recognized: (i) the pre-melting stage is defined by the isorientation of plurimillimetric biotite plus minor white mica lamellae defining the main foliation; (ii) the migmatitic stage corresponds to neosome crystallization (Pl + Qz + Bt + Kfs ± Crd) within microdomains parallel to the main foliation. Moreover, EMPA microchemical analyses were performed to derive bulk-rock composition, to obtain preliminary P-T estimates from conventional geothermobarometry methods and to check for the presence of zircon or monazite crystals suitable for future geochronological analyses. This study raises new questions about the role of these high-grade partially melted rocks within the Boulder Creek batholith. Geochronological (e.g., U-Pb zircon and monazite dating) and further geochemical analyses, and a comparison with migmatized rocks near the outer margin of the batholith will be performed to understand whether these rocks are the source of the melt from which the Boulder Creek batholith originated or if they are instead xenoliths belonging to the country-rock.

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Tectonic setting and magnetic fabric of the Central Bohemian dike swarm

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Keywords: anisotropy of magnetic susceptibility (AMS), Bohemian Massif, crustal extension, dike swarm.

The early Carboniferous (ca. 354–337 Ma) Central Bohemian Plutonic Complex is a 3200 km2 continental magmatic arc developed in response to subduction of the Saxothuringian lithosphere beneath the Teplá–Barrandian microplate in the center of the Variscan Bohemian Massif. The magmatic arc is cross-cut by abundant dikes that form a major ʻCentral Bohemian' dike swarm. The dike compositions include amphibolite–biotite granodiorite, granodiorite porphyry, syenite porphyry, diorite porphyry, granite porphyry and aplite, but also mantle-derived lamprophyres (especially minettes). The dikes that intruded the oldest, 354 Ma Sázava suite (calc-alkaline) are oriented ~NW– SE whereas those that intruded the 346 Ma Blatná suite (high-K calc-alkaline) are oriented ~WNW– ESE to ~E–W none of this are found in younger ultrapotassic plutons (343–340 Ma).To examine the mechanisms of magma flow both within the individual dikes and on a regional scale in the ʻCentral Bohemian' dike swarm, we used the anisotropy of magnetic susceptibility (AMS) method. In all sampled dikes, the AMS revealed low to medium anisotropy and mostly oblate fabric defined by paramagnetic carriers. In terms of orientation, the dikes are characterized by what has been referred to as the normal fabric, defined by a steep, dike-parallel magnetic foliation (dip >60°). Some dikes, however, reveal two distinct magnetic lineations: steeply- plunging and subhorizontal whereas other dikes exhibit only subhorizontal lineation. We interpret the internal dike fabric as recording vertical magma ascent converted to horizontal dike-parallel (? divergent) flow. On a regional scale, the older NW–SE dikes record arc-parallel pure-shear dominated tectonic stretching, whereas the younger ~WNW–ESE to ~E–W are oblique to the magmatic arc axis and record a dextral shear component (transgression) and a change in the regional stress field during the onset of orogenic collapse in the Bohemian Massif at around 346-340Ma.

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Relationships between magma emplacement, tectonics and metasomatism in late Variscan granitoids (Peloritani Mountains, southern Italy)

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Keywords: late-Variscan granitoid magmatism, deformation microstructures, shear zones, alkali metasomatism, southern Italy.

Deformation microstructures recorded in late-Variscan trondhjemites (c. 310 Ma) and granites (c. 300 Ma) from the the Peloritani Mountains in NE Sicily (Fiannacca et al., 2019, 2020) revealed for the first time that shearing affected both granitoids during their cooling, from submagmatic (T > 650 °C) to low temperature solid state conditions (T < 450 °C) (Fazio et al., 2020). Granitoids usually exhibit a largely preserved magmatic texture, 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, indicate deformation in the presence of late-Variscan melt, thus constraining the activity of the shear zone during the post-collisional magmatic stages of the Variscan orogenic cycle. Submagmatic deformation microstructures were largely overprinted by progressive lower temperature microstructures during cooling of the granitoid bodies. 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 deeper crustal levels (c. 0.5 GPa), and in the younger granites, intruding the trondhjemites after their exhumation at relatively shallower depth (c. 0.3 GPa). Shear-zone related deformation also played a role in facilitating fluid infiltration and associated alkali metasomatism responsible for significant petrographic and geochemical modifications in some of the youngest granites, some of which were turned into metamorphic trondhjemitic rocks (Fiannacca et al., 2020). Evidence of the link between shearing and metasomatism is provided by widespread examples of secondary plagioclase growing around sigmoid porphyroclasts, or along micro-shear zones, marked by significant tectonic grain size reduction that produced an increase in the rock permeability and, at the same time, of the surface- controlled rock reactivity.

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Insights from AMS study on tectonic evolution of the Serre Batholith (Southern Italy)

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Keywords: AMS (anisotropy of magnetic susceptibility), fabric, granites.

Serre Batholith is a sheeted-like Late Variscan complex, constituting the intermediate portion of a tilted and roughly uninterrupted section of continental crust exposed in central Calabria. Its building and structural evolution could be related to deep-seated strike slip shear zones dynamics as a consequence of a crustal thickening stage linked to the final amalgamation of Pangea. As a result, some of the granitoids have variously recorded meso- and microscopic deformation-related structures indicating oriented stress affecting the batholith during and after the emplacement of the magmatic bodies. However, granitoids do not always develop visible foliations or lineations, making fabric analysis often ineffective or completely impractical on apparently isotropic granite rocks. Anisotropy of Magnetic Susceptibility (AMS) technique was employed to shed light on the interplay between tectonics and granitoid magmatism, particularly to investigate relationships between shear zones, mechanisms of emplacement and structural evolution of the Serre Batholith. AMS analysis was performed on oriented samples collected from 132 sites distributed throughout the study area. The mean strike of the magnetic foliation is recorded to be NE-SW. The magnetic lineations are distributed on the magnetic foliation with the plunge varying from NE through subvertical to SW. These first results indicate the possibility of a superposed deformation in the study area. Magnetic lineation and foliation maps reveal presence of domains with steeper plunge and dip amount in the Serre Batholith. All these orientation data are being compared with magnetic fabric intensity and available field data from the metamorphic host rocks to discuss the regional tectonic evolution of the Serre Batholith.

Segregation and extraction of late magmatic melt and fluids in mushes: experimental approach at high pressure

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Keywords: plagioclase fabric, magma rheology, experimental deformation, strain partioning.

The physical mechanisms of crystal-rich network and deformation-assisted melt extraction from magmatic systems are poorly understood. In particular, how strain localizes in mushes (i.e., mixture of crystals and silicate liquid whose mobility is inhibited by a high fraction of solid particles) and how this localization can control the segregation and the extraction of the melt from the crystal network remain undetermined. In this study, we performed syn-deformational melt-extraction experiments on haplotonalitic magma using the gas-medium Paterson apparatus.

Four samples with a composition of 68.9 wt. % SiO2,19.6 wt. % Al2O3, 8.0 wt. % Na2O and 3.5wt. % CaO plus H2O were synthesized using an internally heated pressure vessel (P: 300 Mpa). The purpose was to create hydrous (3 wt% H2O) mushes composed of euhedral plagioclases crystals covering the expected extraction windows phase (ϕ: 0.52 – 0.58, 700°C<T<800°C). Torsion experiments were then carried out with a shear strain rate (ẏ) ranging from 1.0x10-4 s-1 to 2.0x10-3 s-1 and a finite strain (γ) ranging between 0.5 and 2.0. Quantitative structural analysis, including shape-preferred orientation (SPO), crystal interaction (CI) and crystal-preferred orientation (CPO) were performed using the SEM and EBSD techniques.

For γ<~1 and low strain rates, a pervasive SPO developed with a main preferred orientation at 45° from the dextral shear direction. For γ >1, isolated domains of touching and similarly oriented grains – either parallel to the shear plane (Y-type bands) or to the compressional direction (C'-type bands) – occurs. With increasing both finite strain and strain rate, these crystal domains thicken and leads to the development of shear zones that progressively extend lengthwise to form an antastomosing network. None of our experiments has evidenced melt migration, whatever in the main pervasive fabric or in the subsequently developed shear zones.

We conclude that: 1) initiation of strain localisation in magmatic mushes begins in discrete crystal orientation domains, contact interactions of which favour stress propagation over the crystal network; and 2) melt extraction is not achieved in these mushes. This suggests that higher crystal content is possibly required, which will be tested in the near future.

Multi-scale perspectives to strain partitioning within partially molten crust: weakening or strengthening behaviour?

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Keywords: melts, deformation, strain partitioning.

Current prevailing models predict a feedback relationship between deformation localisation and melt fraction, so that deformation zones focuses in areas of higher melt fraction, with further melt migrating into active deformation zones from adjacent volumes. In these models, melt fraction controls where and how strain partitions, i.e. the higher the melt fraction, the weaker the bulk rheology. Whilst this seems to be the case in certain, fairly local conditions, much of the migmatitic middle/lower crust shows much more complex behaviour.

In this presentation, I will show examples at various scales where deformation and rheology of partially molten bodies is not controlled solely by melt fraction. Particularly at higher melt fractions (over c. 15%) the amount of melt seems to be of secondary importance to other factors in terms of how the body deforms: fabric organisation and fabric heterogeneity, melt crystallisation rate, grain size, or strain rate are equally, if not more, important in controlling deformation style and strain partitioning. I will focus on crustal-scale considerations of melt fraction versus strain rate: the observations imply that migmatites with high melt fraction may ultimately strengthen, not weaken, the crust during orogenic compression. This has profound implications to modelling of the orogenic lithosphere and how lithospheric-scale strain partitions during orogenic compression.

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Granite plutons as orogenic strain markers

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Keywords: anisotropy of magnetic susceptibility (AMS), granite, plate kinematics, pluton, tectonic strain.

Granite plutonism and large-scale crustal deformation seem to be closely linked in both accretionary and collisional orogenic belts, however, many issues of these complex interactions and feedback relationships still remain poorly understood. The existing views vary between two end-member scenarios, one invoking tectonic deformation as the main control on plutonism at all crustal levels, whereas the other considers plutonism and deformation as more or less independent processes just overlapping in space and time. On a large scale, plate motions and orogenic deformation clearly control the input and melting of fertile lithologies and hence magma fluxes, compositions, and crustal growth or recycling during orogenic evolution. On the other hand, the three-dimensional pluton shapes, no matter how problematic they are to establish, and emplacement processes are not unique to tectonic setting and magma ascent and emplacement occur at significantly different rates (mostly faster) than tectonic deformation. Based on a large body of structural data from granite plutons that have accummulated over the past decades, the interplay between plutonism and tectonic deformation then seems to be most unambiguously recorded by mineral fabrics in the pluton interiors, an observation that has been strongly supported by application of the anisotropy of magnetic susceptibility (AMS). The AMS method is capable of revealing an incredible level of detail, especially in combination with mathematical modeling, as to the type, kinematics, and intensity of finite strain recorded by the magma. In this context, one of the most intriguing discoveries are multiple fabrics within a single pluton, which in most cases reflect heterogeneous superposition of tectonic strain onto earlier intrusive/emplacement related strain. Porphyritic granites are particularly informative as to the grain-scale mechanisms and magma rheology during tectonic overprinting and point to a general model, in which magma is emplaced fast at upper crustal levels as a mobile, melt-dominated suspension/mush, but then stalls as a rigid crystal–melt framework for a prolonged period of time. In this framework, phenocrysts are locked while small grains (e.g., magnetite, biotite) are still easy to reorient in melt pockets via melt-aided grain boundary sliding. Map-scale fabric patterns suggest that plutons behave as weak inclusions in the crust during this period and are extremely sensitive to record increments of regional tectonic deformation within the orogenic belt, and in some instances also far-field plate motions.

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Melt softening driven return flow of UHP metagranitoids in continental subduction channel

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Keywords: continental subduction, melt weakening, granular flow, magnetic fabrics.

Weakening of rocks by interstitial melt during partial melting is regarded as a significant process that drives dynamics of orogenic systems and exhumation of subducted upper crust. The microscale to mesoscale mechanisms responsible for melt enhanced weakening and melt transfer in high pressure anatectic rocks are still a matter of debate. To address the mechanisms coupled melt migration and deformation at high pressure conditions, we have focused on a section of high pressure to ultra-high pressure continental crust that was subjected to continental subduction in the Variscan Bohemian Massif. The section reveals anatectic banded orthogneisses interlayered with migmatitic granofelses and granulites within a single deformation fabric related to the prograde metamorphism. Pressure-temperature conditions for the banded orthogneiss on the western end of the section were estimated at 9 kbar and 700°C, while granofels and granulite reveal much higher pressures of 15 kbar at 760°C, and 15-16 kbar at 775-840°C, respectively. Coesite bearing garnets in granulites at the eastern end of the profile suggest ultra-high pressure conditions. We show that the granofels layers represent high strain zones and reveal traces of localized porous melt flow that infiltrated the host banded orthogneisses and crystallized melt in the grain interstices. The structures along this anatectic sequence reflect the detachment folding along the melt coated deformation fabrics, associated with development of fold axial cleavage and subhorizontal intersection lineation. In the fine grained mylonitic banded orthogneiss and in the UHP granulites, this intersection lineation is rotated to vertical direction. This is interpreted in terms of return flow and decoupling of the subducted portions of the anatectic sequence from the subducted slab. Fabrics in the granoblastic granofelses and granulites are identified from principal directions cluster patterns of the anisotropy of magnetic susceptibility (AMS). We propose that transfer of melt along the high strain zones in the anatectic sequence was responsible for significant weakening of the entire anatectic multilayer. This weakening resulted in exhumation of the deeper parts of the sequence by detachment folding, imbrication and backflow of the HP to UHP crustal slices.

S8.

Innovative and classical approaches in geosciences

Conveners & Chairpersons

Fazio Eugenio (University of Catania)

Grasemann Bernhard (University of Vienna)

The importance of structural data in constraining 3D implicit structural models: the Northwestern Alps case study, Italy

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Keywords: Westernalps, 3D structural model, Aosta Valley.

The Northwestern Alps are one of the most studied and well-known orogenic areas worldwide, exposing a variety of challenging geological structures. However, no updated 3D model of the area exists, due to difficulties in representing the complexity given by polyphase ductile and brittle structures. In the context of the Italian-Swiss Interreg RESERVAQUA project, a new 3D structural model of ca. 1300 km^2 is being built, allowing many important implications on the large-scale tectonic interpretation of the area, and other applications such as studies of circulation and storage of deep-water resources hosted in the bedrock.

Input data is represented by a high-resolution geological database and one key point in our modelling strategy was aimed at taking full advantage from the abundant structural data. This is not straightforward since commercial 3D modelling software is mainly aimed at hydrocarbon reservoirs and do not allow exploiting this kind of data. Our analysis started defining homogenous structural domains, characterized by roughly homogenous foliations (in terms of metamorphic assemblages and orientation) and/or fold axes. Structural data within these domains have been spatially averaged over grids with variable resolution, applying statistical analysis tools allowing to assess the cylindricity in different structural domains. A more or less traditional, but quantitative, conceptual interpretation has been carried out by projecting onto vertical cross- sections the structural field data and map traces of stratigraphic and tectonic elements. This projection was performed along vectors defined for each homogeneous domain in the orientation analysis. Interpolation of 3D surfaces using advanced implicit algorithms follows, with both field data and the conceptual interpretation in vertical cross-sections as constraints.

Ten structurally homogeneous domains have been defined, leading to a clear and objective distinction of sections of the orogenic wedge that are characterized by different tectonic styles. These fall in three macro-domains: (i) an internal Austroalpine-Upper Penninic domain with sub- horizontal nappe boundaries, greenschist to eclogitic peak metamorphism and diffuse collisional greenschist re-equilibration, and both Oligocene and Miocene brittle normal faults striking NE- SW and NW-SE, (ii) the intermediate domain represented by the Grand St-Bernard nappe system, with blueschist peak metamorphism, diffuse greenschist re-equilibration and mainly Miocene brittle faults striking NW-SE, and (iii) an external system with low-T greenschist peak metamorphism, foliations consistently SE-dipping, relatively young semi-brittle thrusts and no Miocene or Oligocene normal faults. In the whole area, fold axes are sub-horizontal and oriented NE-SW or NW-SE.

In this contribution, we focus on examples that are explicative of the geomodelling workflow that can be applied in this tectonic area, and we show how the abundancy of structural data, together with the rugged topography, can compensate for the absolute lack of subsurface data.

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Predicting hydraulic properties in poly-deformed basement rocks with an outcrop analogue approach

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Keywords: outcrop analogue, DOM, photogrammetry.

Estimating the hydraulic properties of a fractured geofluid reservoir remains a challenging problem since boreholes fail to provide continuous spatial information, while geophysics lack in resolution and small discontinuities cannot be detected. In this context, the concept of outcrop analogue plays a central role in the study and modelling of the subsurface fracture networks.

Thanks to the improvement of remote sensing techniques such as photogrammetry or laser scanning, large-scale, high-resolution datasets called Digital Outcrop Models (DOMs) allow collecting huge fracture datasets that have greatly improved the quantitative characterization of fracture network parameters.

Here we present a study carried out on outcrops of fractured gneiss, prasinites and calcschist of the Dent-Blanche Nappe and Combin Zone, exposed on the Italian side of the Cervino/Matterhorn in Valtournenche.

In this area, the regional-scale brittle tectonic events consist in a NW-SE extension, developed in the Oligocene (D1), followed by a NE-SW extension in the Miocene (D2) (Bistacchi & Massironi, 2000; Bistacchi et al., 2001). Detailed interpretation carried out on DOMs returned sets of joints and shear fractures that can be easily attributed to the regional-scale deformation stages. In addition, fractures interpreted on DOMs clearly show the expected abutting relationship between phases D1 and D2.

Recognizing regional-scale fracture sets in our outcrops allows us to extend the results of our statistical characterization at the regional scale, and in the subsurface, fulfilling the requirements of a valid outcrop analogue that can be successfully applied to the prediction of hydraulic properties at depth.

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The importance of structural inheritance in polideformed rocks

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Keywords: fold, foliation, fracture, shear zone, strain partitioning.

The phenomenon of tectonic inheritance, though evident at multiple scales, has been so far mainly invoked at lithospheric scale (e.g. Tommasi & Vauchez, 2001; Şengör et al., 2018).

This work aims to show how important is the influence of inherited structural features in the development of younger ones at regional to outcrop scales. We present some case studies of polideformed rocks from the Variscan basement of NE Iberia, complemented with a review of other published field and experimental studies. The focus is put on the role and effects of preexisting non-interfacing surfaces in subsequent deformation events, either progressive or polyphase. Two main types of non-interfacing surfaces will be discussed:

Mechanical anisotropies developed by ductile flow and defined by grain-preferred orientation such as in LS-tectonites (e.g. foliations). Examples are provided to illustrate the role of inherited foliations on later strain localization, distribution and partitioning, and demonstrate how previous fabrics can control local strain and kinematics, which in consequence significantly deviate from the regional deformation framework (Carreras et al., 2013).

Fracture surfaces which are not penetrative at the micro-scale (e.g. joints). Fractures form another important mechanical weakness that can be exploited by later deformation under ductile conditions, leading to folded and/or ductily sheared joints (Pennacchioni & Mancktelow, 2007; Carreras & Druguet, 2022). Different examples of folding instabilities affecting previous joints and the associated intervening rock lithons will be described. Moreover, examples of nucleation of kink-bands and ductile shear zones on previous joints will be presented and discussed in terms of comparison with other existing models.

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The use of 3D virtual outcrop models for teaching purposes: an example from Cap de Creus folded quartzites

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Keywords: digital field mapping, shear zone, folds, quartzite, 3D scanning.

In recent years, it has become quite common to use new learning methods even in academic courses focusing on geology, based on virtual reality and 3D reconstructions at all scales, from volumes of several cube kilometers to micro tomographic renderings of a few micrometers. Moreover, Covid's restrictions have pushed towards the creation of virtual libraries of museum samples (rocks/minerals/fossils), and it is quite common to share or publish these types of 3D, VR and AR content on the websites of 3D modelling platforms (e.g. Sketchfab). The increasing availability of sensors for consumer users makes it possible to capture 3D scenes by means of Structure from Motion (SfM) techniques even with devices that are now quite common (e.g. smartphones or tablets). The 3D model presented here is a few meters square area of an exposure showing a clear interference folding pattern in the Culip quartzites (Carreras & Druguet, 2019) outcropping in the Cap de Creus area (Southern Pyrenees - Spain; Ponce et al., 2013).

We performed a rapid digital mapping (continuous camera acquisition time of about 5 min - 288 images) of the structures of the folded quartzite layers by walking around the outcrop with a tablet (iPad-Pro 11 gen.) running a scanning freeware application (3D Scanner App TM) obtaining a textured 3D model with good resolution (52000 vertices, 84000 faces) and high-quality details (file size 506 Mb). The orientation of the structures (foliations, fold axes) has good accuracy and are consistent (satisfactory overlap) compared to data collected manually with the traditional hand-held bearing compass.

Our test demonstrates how these new approaches can be an effective extra-learning/teaching tool both in the classroom (measurement exercises with the compass - comparison with virtual models) and in the field (in addition to other applications of digital compass-clinometer for gathering geological data - e.g. Move Clino app - already largely used on mobile devices, which are extremely useful for mapping geological boundaries, collecting the orientation of mesoscopic-scale structures directly in the outcrop). In addition, on extremely windy days, when it is not possible to fly a drone, this represents a valid alternative method for acquiring 3D surface models of relatively small and easy access exposures (max. volume of about 10 m^3).

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Applying a triclinic transpression model to a complex high strain zone at Cap de Creus (Eastern Pyrenees). Preliminary results

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Keywords: Cap de Creus, kinematic models, shear zone, strain partitioning, 3D deformation.

The interpretation of complex mid- to deep-crustal shear zones requires thorough 3D structural and kinematic analyses. The further application of analytic kinematic models may be a good complementary approach. In this work a triclinic transpression model has been applied to a complex high strain zone, which developed in high-grade schists from the north Cap de Creus peninsula during the Variscan D_2 event, a dextral transpressive regime under NNW-SSE bulk crustal shortening, involving sub-vertical extension and subhorizontal shearing. The triclinic transpression model (Fernández & Díaz-Azpiroz, 2009) has been tested in Culip- Culleró, an area in the NE of Cap de Creus where zones of low to high strain are continuously exposed. Heterogeneous strain is evidenced in the schists by the progressive increase in fold tightness and clockwise rotation of both S_1 and S_2 foliations towards the ENE-WSW steep boundaries of the higher strain zone (Carreras & Druguet, 1994; Druguet et al., 1997).

The predictions of the model in terms of finite deformation depend on the value of its main controlling parameters: the pitch of the simple shear-direction (angle), the extrusion obliquity (angle , the angle between the dip direction of the shear zone boundary and the maximum lengthening of the coaxial component of flow, i.e. the extrusion direction), and the kinematic vorticity number (W_k). The model fits well in medium and in high strain domains where D_2 fabrics (S_2 foliations and L_2 lineations) are prevalent over the structures inherited from previous deformation events (bedding-parallel S1 foliation). Instead, poorer adjustment is observed in low strain domains of non-transposed previous fabrics. As the qualitative intensity of the deformation increases, a decrease in the (from 30ºW to 10ºW) and angles (from 20ºE to 0º), and an increase in W_k (from 0.71-0.81 to >0.9) have been found. Therefore, the flow tends to be less triclinic and closer to simple shearing in the most deformed zones. These preliminary results will allow constraining both the direction of relative displacement between the blocks separated by the high strain zone and the amount of extruded material.

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Digital Outcrop Model (DOM): method v aim

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Keywords: digital outcrop model, structure for motion, drone, GPS.

Today, virtuality and digital modelling have become an essential part of our daily life. In the last few years, the global Covid-19 pandemic has increased demand for virtual models to enhance education, tourism, and enterprises. Photogrammetric Structure from Motion (SfM) is a fast and relatively low-cost methodology to generate highly accurate 3D models, as well known as Object files. In geology, Digital Outcrop Models (DOMs) are part of the virtual world, and they are commonly generated for educational, field-work and trips, as well as research purposes. Although Unmanned Aircraft Vehicles (UAVs) and Lidar are usually fostered, new technologies are constantly generated to allow a friendlier and versatile use of such tools. However, are UAV and Lidar the most accurate and precise instruments for DOMs? Can cheaper resources, such as smartphone apps or cameras, be a comparable or even better substitute for surveys? Here, we share multiple acquisition methods applied in selected outcrops around Italy to evaluate their accuracy and reliability in representing reality. We compare models generated by drone, camera, and lidar acquired images, and the benefit and limitation in employing Ground Control Points (GCPs) and Check Points (CPs) are here tested. Our results show strengths and weaknesses of each method, highlighting that the acquisition choice rely fundamentally on the goal of the project.

Using virtual outcrops to investigate strain compatibility when thrusts deform stiff beams – a new model for thrust fault formation

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Keywords: thrusts, multilayers, strain, virtual outcrops, rheology.

In conventional models of thrust fault formation, thrusts quickly propagate upwards through a multilayer from a base detachment, branching off old faults at depth with a fault-bend fold forming in the hanging wall (Dahlstrom, 1969). This model commonly fails to match up to actual geological structures. Conversely, in a stiff layer thrusting model, the thrust originates and localises in mechanically competent beams as ramps and the thrust tip propagates both up and down slowly to create a linked fault system (Eisenstadt & De Paor, 1987). This model has had few tests at outcrop level, so development of a singular model which can be applied across thrust systems is necessary.

Using field and photogrammetric mapping, a series of thrust multilayers are investigated to assess the relationship between rate and path of tip propagation, and the transition between compatible and incompatible strain due to abrupt changes in rheology. On fieldwork, images are taken using a drone and a handheld DSLR camera, with a 3D photogrammetric model produced on Agisoft Photoscan Professional. Combined with structural measurements taken in the field and 3D model interpretations from Virtual Reality Geological Studio (VRGS) and Midland Valley's Move software, the outcrops are examined to produce a structural development model for the outcrop

In the UK, thrust structures in the Old Red Sandstone are ideal test multilayers as they contain deformed competent sandstone beds encased in cleaved mudrocks. Field and photogrammetric mapping has been applied to the St Brides Haven outcrop on the west coast of Pembrokeshire in SW Wales, a little studied outcrop 10m high which exposes an open fold pair typical of Variscan thrust deformation (Hancock, 1981). The low cliff allows for detailed mapping of a duplex structure within an Old Red sandstone-mudstone multilayer. The outcrop has an abrupt rheological change where faults are confined close to a strong sandstone beam up to 1m thick, with characteristic fault spacing along the beams and a developed cleavage in the mudrocks above and below the beams. There is evidence of sedimentological controls on thrust fault growth and deformation, which are linked to variations in rheology and cross bedding features. The cleavage trajectories in the mudstones vary into the beam and are offset by the faults, indicating an irregular distribution in shear strain.

The purpose of this work is to compose a new model for thrust formation from outcrop templates to enrich styles of deforming multilayers and correct bias from a standard model of thrust formation, as abrupt changes in rheology are highly likely in most geological multilayers.

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Tectonometamorphic development of the Eckergneis Complex (Harz Mountains, Germany)

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Keywords: granulite metamorphic facies, pseudosection calculation, tectonic emplacement.

The Eckergneiss Complex (EC) of the Harz Mountains is a Variscan high-grade tectono- metamorphic unit that is surrounded by post-Variscan intrusions as well as by a Paleozoic sedimentary rock sequence of very low metamorphic grade. Peak metamorphism of the EC reached upper amphibolite to granulite facies grade at approximately 328-313 Ma as revealed by U-Th-total Pb dating of monazite (Appel et al., 2019). The main foliation is overprinted by partial melting and static recrystallization of the dynamic fabric as well as by a few localized migmatitic shear zones. The NNW-ward dipping main foliation is associated with a preferentially WSW-ENE striking stretching lineation and roughly parallel fold axes of isoclinal to tight folds. During exhumation and tectonic emplacement from the granulite facies metamorphic condition to the ambient S to SW-ward dipping very low-grade metamorphic rocks of the Rhenohercynian domain the EC was deformed by close to open folding and localized shear zones. After the Variscan orogeny and exhumation, the post-tectonic intrusions caused a marginal contact-metamorphism.

Exact p/T-conditions in relation to the deformation of the EC remain unclear. Pseudosection calculations were carried out on a sillimanite-biotite-garnet-cordierite gneiss (kinzigite) and a quartz-cordierite(pinite)-feldspar-granoblastite sample using Theriak-Domino. They indicate a prograde metamorphism at approximately 750-800°C and 500-550 MPa that is overprinted by second static metamorphism at approximately 670-720°C and 450 MPa on an anticlockwise p/T-path. This is in accordance with the presence of sillimanite and inclusions of spinell as well as microstructures of partial melting indicating previous lower granulite facies metamorphic conditions at least for some parts of the EC. Hence, the main foliation and stretching lineation were already formed under prograde metamorphic conditions. After peak temperature and pressure, at least the kinzigite sample was quite penetratively overprinted under amphibolite facies conditions. The relatively low pressure and high temperature metamorphic conditions together with the range of monazite age data indicate a very high thermal gradient for the Variscan lithosphere of the EC that lasted probably for at least 10-15 Ma. This corresponds to the so-called regional contact metamorphism in Variscan rock units of the Pyrenees (e.g., Mezger & Regnier, 2016). Final exhumation and cooling of the EC to very low metamorphic grade at upper crustal conditions need to have taken place quickly along localized detachment faults, e. g. the Acker-Bruchberg Thrust Zone, until the end of the Variscan orogeny.

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Hyperspectral outcrop characterization for structural mapping

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Keywords: digital outcrop, hyperspectral, structural mapping, 3D modelling.

Digital outcrop models have become a powerful tool for detailed structural mapping (Bemis et al., 2014), as they allow geological exposures to be characterized in unprecedented detail while simultaneously mitigating access limitations that hinder conventional mapping approaches. In this contribution we present an emerging workflow that fuses digital outcrop data with high resolution ground- and UAV- based hyperspectral imaging products to better discriminate key lithological units (marker horizons) and alteration trends (Lorenz et al., 2018; Kirsch et al., 2019). In some settings, hyperspectral data allows key mineral abundances to be mapped directly to create qualitative mineral maps (e.g., Thiele et al., 2022), however for structural mapping purposes the identification of distinctive marker horizons can be sufficient (e.g., Thiele et al., 2021). We illustrate this workflow with several examples from the Iberian Pyrite Belt (Spain), where the hyperspectral data helped constrain the geometry of deformed volcanic units hosting massive sulphide mineralization. Finally, a preliminary approach for combining (hyperspectral) digital outcrop data and 3-D interpolation algorithms to derive 3-D structural models of open-pit mines is discussed.

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How should we translate Structural Geology and Tectonics-specific terms to other languages?

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Keywords: dictionary, terminology, database, translation, ontology.

Most Bachelor of Sciences classes are taught in the native language of the institution, but to prepare the students for any international scientific career, it is critical to teach them the technical terms accepted by the community. In Structural Geology and Tectonics many technical terms that were originally defined in English can be ambiguously translated to other languages. For example, if students (and teacher likewise) look up terms like tension and stress in a German dictionary, they would find *Spannung* as the translation for both. Similarly the words *extension* ($e = \delta l/l_0$) and *stretch* ($S = l_1/l_0$), which are very distinct parameters, could both be translated in German to *Dehnung.*

We suggest that it would be valuable and timely to develop a community-editable database containing key entities and their relationships and translations within the fields of Structural Geology and Tectonics, which would serve as a resource for translation as well as knowledge-building.

In more precise terms, we propose the development of a multilingual domain-specific ontology for Structural Geology and Tectonics. In information science, domain-specific ontologies consist of a queryable database of entities related to a particular field and their relationships. The proposed project may thus be divided into three phases. First, we define a set of possible relations between entities in the geological domain (for example, *relation:isContainedWithin*). In the second phase, we exploit existing digital resources (such as Wikipedia and Wikidata) in tandem with computational linguistic methods to populate a SPARQL database with entities and their relationships (*entity:striation* + *relation:isContainedWithin* + *entity:fault plane*). In the third phase, a web application is developed that allows display and public editing of the created data.

While there have been recent efforts to build ontologies for geological knowledge, none offers comprehensive translations, nor a publicly accessible and user-friendly interface for exploring and/or extending the ontologies' content. We argue that open access and editing permissions will facilitate the construction of a large and high-quality dataset, and that a web platform for querying the data will make the database useful to both students and researchers in the Structural Geology and Tectonics fields.

We aim to publish the developed dataset via the International Association for Structural Geology and Tectonics (IASGT) / Tektask website (http://www.tectask.org/). This initiative will be aligned with the Structural Geology and Tectonics terminology database initiative of Tektask (http://www.tectonique.net/ttt/). We request that other members of the community contribute appropriate translations in their own languages. We will refine the translated terminology over the next 2 years, then seek community validation of the translations at the 2024 DRT conference, followed by publication.

Brittle microstructures of experimental faults in phyllosilicate-granular mixtures

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Keywords: experimental faults, fault fabric, microstructures, friction, deformation mechanism.

Laboratory constraints pose mineralogy, stress, and temperature conditions as the main controlling factors of fault frictional properties. Fault rock fabric also plays a fundamental role, but its documentation is frequently subordinate to the other factors. In fact, despite extensive works on the characterization of the rheology of experimental faults, a systematic link between microstructures, fabric and frictional properties is still rare in literature. Here we present a focused study that integrates microstructural and frictional characterization of four different powdered rocks. Shear experiments were performed on the samples by varying the normal stress (25, 50, 75 and 100 MPa), at both room-dry and water-saturated conditions, thus obtaining a total of 24 experimental microstructures and related mechanical data. For each experimental fault we document its inner architecture, local microstructures and discuss the link with their frictional behavior, here analyzed in the rate and state framework. This work provides an example of the wide variety of brittle fabrics that originate from simulated faults as a function of mineralogy, stress, and humidity conditions. For this work, we sampled shear zones of the basement rocks of the Central Apennines. Rocks were then powdered to simulate fault gouges. Their composition is dominated by variable amounts of quartz and phyllosilicates. The relative amount of the latter strongly affects the frictional behavior as well as their microstructures, thus individuating: granular-rich gouges and phyllosilicate-rich gouges. Microstructural analysis was carried on deformed samples using a scanning electron microscope in back-scattered mode. Imagery was collected in high resolution to obtain wide panoramas, allowing the study of fault fabric at the sample scale down to the sub- micron scale. Granular-rich gouges are characterized by localized deformation along narrow and discrete shear zones of intense brittle comminution, which separate low strain domains (Y-P-R fabric). Conversely, phyllosilicates-rich gouges produce a pervasive foliated fabric characterized by distributed deformation (C-S-C’ fabric). Increasing normal stress conditions enhance the grain size reduction and favors the interconnectivity of phyllosilicates in granular-rich gouges, intensifying the fabric. Water content mainly favors sliding along phyllosilicate foliae, enhancing the formation of a pervasive fabric. Frictional properties well match the microstructural observations. Granular- rich gouges have high friction, high healing rates and velocity strengthening-to-neutral behavior, which points to the dominance of localized cataclastic processes. Phyllosilicate-rich gouges display low friction, low healing rates and strong velocity strengthening behavior, which is linked with frictional sliding along phyllosilicate foliae and distributed deformation. Second order variations of the frictional parameters are also reflected by the variation of the inner fabric of the experimental faults. For instance, the higher intensity of foliated fabric observed at high stress corresponds to higher rate strengthening behavior and lower healing rates. Our work highlights how a detailed microstructural analysis can strongly support and strengthen the interpretation of experimental studies on rock friction.

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