Waiting for Yorsget Abstract Book

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2021 JUNE 21-22

Dipartimento di Scienze Biologiche, Geologiche e Ambientali – Università degli Studi di Catania (Italy)

Welcome to 'Waiting for Yorsget' web conference (21-22 June 2021)

Dear friends and colleagues,

We have decided to postpone for another year the YORSGET in-person meeting. It will take place in Sicily on 16-21 June 2022 but we settled a two days digital event 'WAITING FOR YORSGET' on 21 and 22 June 2021. This web-meeting represents an attempt, even in a virtual way, to stay in touch with people who have already made a pre-registration as well as other further potential interested people. The digital meeting will be hosted by the SGI (Società Geologica Italiana) web-platform (Gotomeeting virtual room hosting up to 200 people). We are also planning to manage secondary virtual rooms for posters and Q&A slots.

Thank you for participating!

Warmest greetings from the YORSGET 2022 Organising Committee

Rosanna, Rob, Rodolfo, and Eugenio

June 2021

Program

1st day

June 21st 2021, 13:40 CET: Welcome from the Organising Committee

14:00-15:00 CET: Keynotes:

Whitney Behr**: *What's down there? The structures, materials and environment of deep-seated slow slip and tremor***

Haakon Fossen**: *From deep continental subduction to profound orogenic stretching: The Caledonide example***

Q&A and Poster session: 15:00-17:00 CET

2nd day

June 22nd 2021, 14:00-15:00 CET: Keynotes:

Michele Fondriest**: *The shallow internal structure of carbonate-hosted seismogenic faults: constraints from field structural surveys and near surface geophysics***

Mary Ford**: *Rethinking an orogen - a new look at the Pyrenees and how they evolved***

Q&A Poster session: 15:00-17:00 CET

Keynote speakers

Haakon Fossen

Mary Ford

Whitney M. Behr

Michele Fondriest

Haakon Fossen is a professor at the University of Bergen (Norway). His main interest lies in the field of Structural geology and Tectonics, and he is the author of the textbook "Structural Geology"(Cambridge University Press). His research interest covers orogeny and orogenic collapse, rifting, shear zones, transpression, fault growth and subseismic structures, and involves structural field data, remote sensing data, physical modeling, theoretical structural geology and geothermochronology.
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Mary Ford is a field geologist and principally interested on the interactions of sedimentation, erosion and tectonics from outcrop to regional scale in both in orogens and in rifts. Her approach involves mainly field based mapping, sediment logging, cross section construction and sequentialrestoration. She usually works in multidisciplinary projects, collaborating with specialists in many other domains to best constrain processes in time and space. Her main field areas are the Corinth rift, the Pyrenees and the western Alps.
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Whitney M. Behr is Associate Professor of Structural Geology and Tectonics Chair at the Geological Institute, Swiss Federal Institute of Technology, Zürich (Switzerland). Her main research interests are related to Structural Geology and Tectonics. Her research themes deal with subduction zones, Earth's early evolution, heterogeneities along subduction zones, lower crust and lithospheric mantle.
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Michele Fondriest is currently a postdoctoral researcher at the University of Padova (Italy) and will move soon to the University Grenoble Alpes (France) with a Marie-Curie Fellowship. His main research interests are the structure and mechanics of fault zones and their relation to the seismic cycle. He is addressing these topics by combining detailed field characterization of exhumed fault zones (structural geological mapping, 3D-modeling), mineralogical-microstructural-petrophysical studies of fault rocks, and rock deformation experiments.

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YORSGET POSTPONED to 2022!

Sicily 16-21 June 2022 - Visit us at: https://www.facebook.com/yorsget

YORSGET is a TecTask (IUGS) conference aimed primarily at MSc/PhD students, post-docs, and early career researchers in the broad field of structural geology and tectonics. The conference provides a platform for networking and research presentations in a supportive and inspiring atmosphere. The conference consists of keynotes, regular talks, poster presentations, and field trips.

Yorsget 2022 will be the third conference in the series. Sicily has been chosen for the conference as it offers great opportunities for examining the interactions between tectonics, landscape and stratigraphy. As with previous meetings, the conventional presentation days in the meeting are complemented with field excursions to promote discussion. Visit the field trips page for more information.

The first Yorsget was organised at the University of Oviedo, Spain, in 2008. The second conference was held in Montgenevre, French Alps in 2018 https://conferences.leeds.ac.uk/yorsget/.

Other sponsors include: University of Catania, Gruppo Italiano di Geologia Strutturale, Italian Group of Himalayan Geology, Geosciences https://www.mdpi.com/journal/geosciences.

"We look forward for in person meeting in Sicily on 2022 but we hope you will also enjoy this digital one!

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Investigating grain boundaries in quartzites as possible percolation pathways using atomic force microscopy

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Grain boundaries play a crucial role in assisting or resisting fluid flow and studies on their morphology offer insights into mechanisms by which fluids percolate and move through the lower crust. While previous studies have documented grain boundary widths and their variation with depth using Transmission Electron Microscopy (TEM), lateral variations in grain boundary widths have not been previously documented in detail. Our studies focus on determining lateral variations in grain boundary widths in seven quartzite samples from the Rengali Province in India1, deformed and metamorphosed at different metamorphic grades using Atomic Force Microscopy (AFM).

Using the AFM, the average grain boundary widths were found to be significantly higher in mylonitised quartzites deformed under greenschist facies conditions compared to quartzites deformed and metamorphosed under granulite facies conditions. This suggests a correlation between the grade of metamorphism and the structural width of grain boundaries, with higher grade rocks having lower grain boundary widths. Additionally, some grain boundaries appear to contain periodic 'bridge'-like structures across which the grains on either side appear joined together. These bridge structures impart a coherent character to the boundaries across which they are developed and may correspond to the periodic overlap of lattices developed along Coincident Site Lattice (CSL) boundaries.

Force Distance (FD) Spectroscopy using AFM was used as an indirect measure of the hardness of the surface being analysed. From the FD curve it is possible to determine a parameter known as 'Plastic deformation'; This allows us to qualitatively argue that if the intermolecular force at a point is stronger, then plastic deformation should typically be less when we are using same AFM tip and at the same ambient conditions (all analyses are carried out at room temperature and 1 atmosphere pressure). FD spectroscopy of the grain boundary domains reveal that traces of the grain boundaries which contain the bridge structures are typically 'harder' than those without the bridges. Additionally, FD Spectroscopy also allows for the determination of grain-scale elastic moduli within samples. The results of our study show that the grain-scale elastic modulus is higher in the samples deformed and metamorphosed at high grades and lower in samples deformed and metamorphosed under greenschist facies conditions. Therefore, the results of this study show that at higher metamorphic grades, fluid percolation along a grain boundary might be impeded due to decreased structural width and increased coherence.

The C’-c method: A new approach for quantitative kinematic vorticity number estimation using quartz CPO and C’ shear bands

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Keywords: kinematic vorticity, shear zones, crystallographic preferred orientation, C’ shear bands

The sectional kinematic vorticity number (Wn) during deformation can be calculated from the relative orientation between the flow apophyses, A1 and A2. Several methods for estimating Wn use the orientations of structures such as foliations, veins, shear bands, and crystallographic preferred orientation (CPO) as proxies for the orientation of A1 and/or A2. As such, the occurrence of such structures limits it usage to the rocks where they are well represented. The development of additional methods to quantify Wn, using new or different combinations of structures, can help enable usage in more rocks, allowing for more complete vorticity studies.

In this study, we present a new Wn estimation method based on quartz CPO and C’ shear bands. This approach, here called C’-*c* method, is based on estimation of the angle between the flow apophyses A1 and A2 by performing two independent measurements. The tilt angle of a quartz crystallographic preferred orientation (β) and the orientation of the C’ shear bands (θ). Using these two angles it is possible to quantify the sectional vorticity number using the following formula: $Wn = Cos[2(\theta-\beta)]$. Data obtained by applying the C’-*c* method on known shear zones from the Himalaya and northern Sardinia match well the vorticity numbers estimated with other approaches on the same structures. In this study, we also applied the C’-c method to the Abloviak Shear Zone (located in the Torngat Orogen, northern Quebec, Canada) and the Ben Hope Thrust (Caledonides of NW Scotland) obtaining the first vorticity data on these structures. The application of the C’-*c* method to a wide variety of rocks showed that it can be negatively affected by microscale kinematic flow partitioning causing underestimation of the obtained Wn. Careful microstructural characterisation of the specimens, however, can mitigate this highlighting the importance of a detailed study for specimens before any estimate of kinematic vorticity is attempted.

Dissolution process: when does the process start?

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Keywords: stylolites, fluid-rock circulation, permeability, rock dissolution

Dissolution process is a complex phenomenon controlled by several factors (lithology, porosity, stress orientation, environmental conditions, networks of fractures) but in the karst field, compression tectonic structures, as like stylolites, are never been taken into consideration. In the karst field, circulation is commonly associated to extensional feature (as faults and joints), assuming that there can be no fluid pathway through compression tectonic ones. In this context, stylolites play an important role in fluid circulation during carbonate deformation. They are plans of dissolution formed by a pressure solution processes that dissolves the soluble particles leading to an enrichment in insolvable non-carbonate particles (NCP) along their planes. This can potentially reduce the porosity and permeability of the stylolite-bearing rock (Alsharhan, 2000).

Stylolites have an extremely variable shape from the meso- to microscale, with variable porosity and permeability. Because of this, they have a strong effect on regional fluid flow and the formation of proto-karst since they can act as barriers or conduits for flow. The focus of the research is to investigate the starting point of the dissolution and mostly di micro-mechanism to lead to the formation of caves.

In this research we integrated field work with lab analysis.

The field work was carried out in a karst area in the South Italy (Alte Murge), where, using the method of Caine (Caine, 1996), the permeability of the three fault zones was reconstruct. The lab analysis (chemical, petrographic) were performed on selected samples representative of the main 4 different shape of stylolites according to Koehn's classification (Koehn, 2016).

Chemical and petrographic (SEM and FTIR) analysis allowed us to characterize the mineral submicroscopic arrangement of stylolites to determine the role of NCP and the pores distribution in and around the stylolites on fluid circulation. CT analysis were carried out to characterize the spatial distribution of the voids and visualize which pores are connected. Despite the common thought, the presence of clays inside of the stylolite's planes, doesn't prevent the initial dissolution process.

We present the first considerations between stylolites, pore networks distribution and karst formation.

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Reaction-enhanced ductile deformation during carbonation of serpentinized peridotite

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Carbonated serpentinites (listvenites) in the Oman Ophiolite record mineralization of several GT of CO_2, but the mechanisms providing permeability for continued reactive fluid flow are unclear. Here we report evidence for localized ductile deformation during serpentinite carbonation in samples of the Oman Drilling Project Hole BT1B (Kelemen et al. 2020), based on observations from optical microscopy, cathodoluminescence microscopy, SEM, electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM), in segments of the core that lack a brittle overprint after listvenite formation (Menzel et al., 2020). Listvenites with a penetrative foliation have abundant microstructures related to crystal growth and indicate that the carbonation reaction occurred during tectonic deformation. Folded magnesite (magnesium carbonate) veins mark the onset of carbonation, followed by deformation during growth of magnesite. Undeformed magnesite overgrowths and euhedral quartz growth zoning indicate that deformation stopped when the reaction was completed. We propose deformation by dilatant granular flow and dissolution-precipitation assisted the reaction, while deformation in turn was localized in the weak reacting mass. Lithostatic pore pressures promoted this process, creating dilatant porosity for CO_2 transport and solid volume increase. This feedback mechanism may be common in the cold leading edge of subduction zones, allowing intense fluid-rock interaction in mantle rocks.

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Overprinting relationships between fault rocks: an example from high pressure metagranitoids in the Gilba Valley (Dora Maira Massif, Western Alps)

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Keywords: mylonite, pseudotachylyte, cataclasite, Dora Maira Massif, Brossasco-Isasca Unit

In this contribution the relationships between mylonite, cataclasite and pseudotachylyte, outcropping in the in the Brossasco-Isasca Unit, in the south-western portion of the Dora Maira Massif (Western Alps) have been analysed (Cosca et al., 2005). A multi-scale structural geology approach, starting with the compilation of a geological-structural map of the area (at the scale of 1:5000) highlighted the occurrence of a deformation gradient. Emphasis was given on the observations, and on the overprinting relationships, of the different types of sheared rock, at the mesoscale, followed by their microstructural/microtectonics characterization of selected samples. The late 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, formed at very shallow conditions, was reconstructed. Different types of mylonitic rocks, developed under general flow conditions as determined through the study of kinematic vorticity (Kurz & Northrup, 2008), showing a top-to-the SW/W sense of shear and associated to during greenschist facies re-equilibration, have been recognized and mapped. Cataclasite and pseudotachylyte, hosted in the mylonitic gneiss (Cosca et al., 2005; Zechmeister et al., 2007), nucleated often (but not always) on structural discontinuities precursors like the mylonitic foliation (Sibson, 1980) or compositianal banding. Interesting overprinting relationships between mylonite, cataclasite, pseudotachylyte veins and foliated/mylonitic pseudotachylyte are described (Zechmeister et al., 2007). These overprinting relationships were linked to different frictional-viscous cycles (Handy & Brun, 2004) in wich several 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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Carbonate reservoirs: Microstructures and petrophysics from Noto Formation cores (Hyblean Plateau, SE Sicily, Italy)

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Keywords: core investigation; fracture; stylolite; carbonate reservoir; Hyblean Plateau; Noto Formation

Cores analysis is widely used for basin modelling and reservoir characterization, in particular, in carbonate deposits where microstructures (fractures, stylolites) behave as fluid flow lines (open fractures) or barriers (filled fractures). Petrophysics, sedimentological, and microstructural analyses from cores and well logs are necessary to understand the correlation between porosity and sedimentary and tectonic structures in reservoirs. In this study, multidisciplinary examinations, carried out on the cores of Eureka 1 well in the Hyblean Plateau (SE Sicily), were successful in characterizing the Noto Formation as well as in outlining the tectonic evolution of the area. The cores come from the Hyblean Foreland, a culmination of the Meso-Cenozoic carbonate sedimentary succession of a largest crustal sector known as Pelagian Block, representing the northernmost margin of African Plate. The upper Triassic Noto Formation, considered the main source and reservoir rock of the Hyblean petroleum system, is composed of limestones, laminites and black shales deposited in an intertidal environment. All measurable parameters, such as bedding, joints, faults, veins, sedimentary and tectonic stylolites (i.e. length, aperture, amplitude, filling, frequency and orientation) were recorded together with sedimentological and petro-structural analyses of rock thin sections. The multidisciplinary analyses revealed that along most of the fractures, mainly filled with carbonate cement, no increase in porosity occurs, whereas the stylolites are partially permeable and therefore not good barriers to fluid flow. Cross-cutting relationships highlight two main tectonic phases: an older, extensional, linked to the Late Triassic rifting, coeval with the opening of the Alpine Tethys; a younger compressional one, linked to the convergence between Africa and Eurasia plates.

Orogenic wedge structure determined by convergence velocity and crustal thickness

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Keywords: Orogenic wedges, numerical modelling, tectonics

As continental plates collide, an orogenic wedge forms to accommodate convergence, resulting in the building of mountain chains. Orogenic wedges' structures depend on the rheology of deformed crustal rocks, controlled by geothermal gradients (Ellis, 1988; Vogt, Matenco and Cloetingh, 2017), bulk composition (Chen *et al.*, 2017; Piccolo *et al.*, 2017; Vogt *et al.*, 2017; Vogt, Matenco and Cloetingh, 2017) and internal friction angle (Ruh, Kaus and Burg, 2012; Dal Zilio, Ruh and Avouac, 2020), as well as convergence velocity, defining the rates at which the wedge strains and the distribution of brittle-ductile deformation (Burov, 2011). Convergence velocity variation is a key component of collision, which implies decreasing, possibly vanishing, rates thereby impacting the structural evolution of orogenic wedge. In this study, we utilise a 2D thermo-mechanical model to investigate the role of convergence velocity on the resulting structures associated with continental collision and the formation of orogenic wedges. The use of a visco-plastic rheology allows rate-dependency to be accounted for through viscous deformation, influencing the structure of the orogenic wedge.

Our results show that orogenic wedges with a constant crustal thickness and constant converge velocity reach a steady state and are characterised in to 3 categories, based on the geometry and internal structure: (1) Plastic wedges, characterised by crustal stacking of the entire crust and no dependency on convergence velocity which are narrow and thick. (2) viscous wedges, characterised by folding of crust and diffuse deformation that are wide and thin and (3) visco-plastic wedges that show diffuse deformation in the lower crust and crustal stacking in the upper crust. The transition among these categories is controlled by the convergence velocity: as it increases, the viscous wedges transition to visco-plastic to plastic. We propose a scaling for the critical velocities as a function of velocity and crustal thickness, which is varied from thinner, continental margins to thicker crusts. The outcomes allow the discussion of the different structures observed in the Alps, Himalayas and Zagros orogenic wedges.

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Influence of basal detachment discontinuities on normal faults evolution: insights from analogue modelling

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Keywords: Analogue modelling, Ductile detachment, Extensional tectonics, Kinematics

Understanding of how normal faults grow is crucial to characterize the tectono-stratigraphic evolution of sedimentary basins, the development of petroleum systems in extensional tectonics, or the hazard related to active seismogenic normal faults. Several studies have modelled extension by using wet clay, layers of loose sand on ductile or on frictional detachments. However, the three-dimensional kinematic evolution of normal faults is still uncertain and questions about the influence of basal discontinuities on fault growth, fault interaction, and relationship between fault length (or seismogenic area) are still not fully investigated.

Two main models have been proposed to explain the growth of normal faults: i) the propagating model, which suggests that faults develop by synchronous increasing of their length and displacement, and ii) the constant-length model, which suggests that faults firstly grow in length, and only once the full-length is reached, they mainly grow by displacement accumulation. A third hybrid model has been proposed by Rotevatn et al. (2019), suggesting that normal faults are characterized by a first stage of fault length propagation and a second stage of constant-length displacement accumulation. However, these authors mainly analysed single isolated faults which might not be representative of more complex extensional systems. Therefore, further work is needed to better understand the growth of interacting normal faults.

In our work, a series of scaled analogue models are used to study the influences of basal detachment discontinuities on the evolution of extensional faults, developed above an inclined basal detachment. A rigid wall was moved to promote extension causing faulting of the loose sand units covering a silicon basal detachment. Three different basal configurations have been modelled: i) homogeneous distribution of the ductile detachment, ii) a transversal boundary which separates the silicon layer from the loose sand, and iii) a sharp, oblique boundary which separated the silicon layer from the loose sand. We performed a pseudo-3D analysis of the extension accrued by faults, measuring the movement of marker points, as if they were actual GPS fixed stations, located at both their footwall and hanging-wall blocks. Results show how the kinematics of faulting strongly depends on: i) the geometry of the ductile-brittle interface respect to the direction of extension, ii) the inclined basal surface, iii) the thickness of the ductile layer. In addition, we suggest that the horizontal extension measured from GPS points, can be sub- or over-estimated if located on rotating blocks.

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Analogue modelling of strike-slip tectonics from basin to structural-scale comparing silica sand and new rock-analogue materials

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Keywords: Analogue modelling; granular materials; rock mechanics; fault damage zone; strike-slip tectonics

Strike-slip fault zones commonly display complex 3D geometries, with high structural variability along strike and with depth and their architecture and evolution are difficult to analyse. In this regard, analogue modelling represents a powerful tool to investigate the structural, kinematic and mechanical processes in strike-slip fault systems at various scales. In detail, dynamically scaled experiments allow the direct comparison between model and nature. The geometrical scale factor defines the model resolution, in terms of model/prototype length equivalence, and depends on the mechanical properties of prototype and model material. Therefore, the choice of the analogue material is critical in scaled analogue experiments.

Granular materials like quartz sands, showing non-linear strain-dependent deformation behaviour similar to brittle rocks, are ideal for the simulation of upper crustal deformation processes. Nevertheless, comparing the geometrical scaling factor of the common analogue materials applied in tectonic models, we identified a model resolution gap for the simulation of fault-fracture processes corresponding to the outcrop scale (1 m – 100 m).

We developed a new Granular Rock-Analogue Material (GRAM, Chemenda et al., 2011) for the simulation of fault-fracture processes at the structural scale. GRAM is an ultra-weak sand aggregate composed of quartz sand and hemihydrate powder capable to deform by tensile and shear failure under variable stress conditions. Based on dynamical shear tests, the new GRAM is characterised by a similar stress-strain curve as dry quartz sand and has a geometrical scaling factor $L^* = L_{model}/L_{nature} = 10^{-3}$ (1 cm in model = 10 m in nature).

We performed strike-slip experiments at two different length scales, applying as model material dry quartz sand and the new GRAM. Digital Image Correlation (DIC) time-series stereo images of the experiments surface allowed the comparison of the developed structures at different stages of dextral displacement above a single planar basement fault. The analysis of fractures localisation and growth in the strike-slip zone with displacement and strain components enabled the comparison of the different structural styles characterising dry quartz sand and GRAM models. The application of the developed GRAM in scaled experiments will provide new insights into the multi-scale investigation of complex deformation processes with analogue modelling techniques.

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Discussing fault reactivation in the Turkana depression (East Africa) using analogue models of multiphase rifting

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

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

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

Deciphering the structural-thermal architecture in the hinterland-foreland transition zone: the case of the Nappe Zone in the Sardinian Variscan belt

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Keywords: Structural geology, RSCM, Variscan basement, Nappe Zone

The comprehension of the structural and the metamorphic evolution of deformed tectonic units is necessary to develop coherent tectonic models of orogens. Collisional belts are characterized by the presence of large-scale nappes and first-order thrusts that complicate the structural architecture of the orogen. The Nappe Zone in the Variscan Belt of Sardinia (Italy) is made of a monotonous sequence of polydeformed low-grade metasediments rich in carbonaceous material (CM), with few metavolcanic rocks and marbles (Carmignani et al., 1994; Montomoli et al., 2018). The Internal Nappe Zone is represented by the structurally upper Barbagia Unit (BU) overthrusted above the Meana Sardo Unit (MSU), belonging to the External Nappe Zone. The boundary between the Internal and External nappes is marked by the Barbagia Thrust (BT; Montomoli et al. 2018), a regional-scale ductile to brittle, shear zone. Although the tectonic setting of the hinterland of the Sardinian Variscan belt, as well as the foreland, is well-studied (see Cruciani et al., 2015 for a critical review), the metamorphism of the entire Nappe Zone, or hinterland-foreland transition zone, remains poorly investigated (Carmignani et al. 1994; Montomoli et al., 2018). Few available thermal data of this sector by illite crystallinity (Franceschelli et al. 1992; Montomoli et al., 2018) point to metamorphic temperatures in the range of 300-350°C. A detailed meso- and microstructural investigation presented in this study allows defining four main ductile deformation phases heterogeneously distributed in both units. Integrating Raman Spectroscopy of Carbonaceous Material (RSCM; Beyssac et al. 2002) thermometry with structural data, we obtain high-resolution structural-thermal cross-sections. The estimated thermal conditions, between 400-500°C, are higher relative to previous estimates in this area, but in agreement with the observed quartz microstructures. The difference in temperature between previous illite data and the presented RSCM data may be explained by the irreversible nature of the process of graphitization (Beyssac et al., 2002), which in most cases allows preserving peak temperature features regardless of the retrograde path. We observe a southward decrease of temperature in both tectonic units. Our data fit well with a scenario of nappe-stacking deformation and subsequent antiformal and synformal structures, shedding new light on the evolution, architecture and configuration of the nappes system, in this portion of the Variscan Belt.

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Passive structural control on skarn ore mineralization: the case study of the Rosas shear zone in the fold-and-thrust belt of SW Sardinia (Italy)

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Keywords: Skarn, mineralization, orebodies, tectonics, fold-thrust belt

The Rosas Shear Zone (RSZ) is a highly strained zone developed under sub-greenschist facies in the Variscan fold-and-thrust belt of SW Sardinia. It lies in the footwall of the Arburese Thrust, a NE-dipping regional thrust that took place during the top-to-the-WSW emplacement of the tectonic nappes over the external zone of the chain. The RSZ is characterized by a penetrative SW-dipping cleavage well-developed in a succession ascribed to the Lower Cambrian-Upper Ordovician. The original bedding is transposed along the tectonic cleavage and a system of anastomosing SW-verging low angle thrusts defines tectonic slices mainly consisting of Lower Cambrian dolostones and limestones embedded into the Upper Ordovician siliciclastic succession. The RSZ was structured near to the crustal brittle-ductile transition, in a depth range of 11.5-13.5 km and a temperature range of 250-300°C. The deformation at these P-T conditions was accommodated mainly by pressure solutions and grain boundary sliding mechanism.

Within the RSZ, the compressive deformation phases are postdated by the intrusion of a NE-dipping, up to 100 m thick gabbro-dyke that can be related to the exhumation phase of the Variscan chain that occurred in late Carboniferous-Permian times.

Several skarn orebodies, consisting of prograde stage (wollastonite, pyroxene, garnet) and retrograde stage (epidote, amphibole, chlorite) mineral assemblages, developed on the carbonate tectonic slices. Occasionally, metasomatism on mafic rocks produces a clinopyroxene, amphibole, epidote, prehnite, titanite, feldspars and armenite assemblage. The ore minerals include mostly Zn-Cu-Pb sulfides such as sphalerite, chalcopyrite, galena; magnetite, pyrrhotite and pyrite are also common. In addition, Ag-sulfides, native Au grains and Co-arsenides have also been identified. The mineralogy of the skarn orebodies seemingly reflects a large-scale hydrothermal fluid circulation at distal environments from the causative intrusion, represented by ilmenite-series, ferroan granites of early Permian (289±1 Ma), intruding the RSZ about 3 km to the E. Accordingly, the high- to low-angle NNW-SSE thrusting structures and the associated pervasive foliation provided the increase of permeability and a large-scale circulation of granite-related fluids. Moreover, given the nature of host- and wall-rocks, the tectonic slices acted as traps for the mineralizing fluids, increasing the reactive potential of the carbonate rocks.

In conclusion, a tight passive structural control for the formation of the skarn-type orebodies of the RSZ can be assumed considering that the mineralization occurred at shallow depth affecting a structural framework previously acquired at deeper crustal levels.

Development of extensive back-thrusting in the Variscan fold-and-thrust belt of SW Sardinia (Italy): geometry, kinematics, and relationships with inherited structures

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Keywords: buttressing, back-thrusts, pre-existing folds, inversion tectonics, structural inheritance

The Variscan fold-and-thrust belt of SW Sardinia consists of two stacked tectonic units, the Iglesiente and Arburese units, separated by the Arburese thrust, the main Variscan structure in this area. The Iglesiente Unit has been overthrusted by the Arburese Unit with a top-to-the-west transport direction during the collisional phase of the Variscan Orogeny, in Early Carboniferous times.

The Iglesiente Unit is characterized by a complex stratigraphic and structural setting because the Variscan deformation overprints previous structures related to the Sardic Phase, a compressional event occurred in Middle Ordovician. Thus, the following superposed structures can be recognized: 1) E-trending Sardic folds characterized by upright limbs; 2) N-trending Variscan inclined folds; 3) Variscan fore- and 4) back-thrusts. The Sardic and Variscan folds gave rise to a domes-and-basins pattern so that the thrusts developed in a non-layer cake stratigraphic succession, cutting across strata whose steepness ranges from horizontal to vertical and the strike varies from parallel to perpendicular to the thrusts.

The main aim of this research is to understand how inherited folds may influence the structural style of a fold-and-thrust belt, focusing in the NW sector of the Iglesiente Unit, where back-thrusts developed extensively.

Field surveys, cartographic and structural analysis and 3D modeling and restoration allowed us to define the geometry, kinematics and displacement of back-thrusts, inferring which relationships exist with the inherited folds.

Our findings suggest that the extensive back-thrusting development is due to the occurrence of the domes that acted as an inherited buttress that prevents the fore-ward propagation of deformation. During their progressive growth, the back-thrusts affect the Sardic folds, that are folds with the axes perpendicular to the back-thrusts strike. According to which part of the fold is cut across, limb or hinge, the back-thrust's shape varies along strike. In particular, the thrust's surface may be either concave upward, in the case the back-thrust affects a synform dipping in the same dip direction of the back-thrust, or concave downward, in the case the back-thrust affects a vertical limb perpendicularly to its strike. Interestingly, depending on these geometries, the displacement along the back-thrusts decreases moving from the hinge to the limb.

Another peculiarity in the study area is the occurrence of back-thrusts with a steepness higher than 70°. 3D restoration demonstrates that such back-thrusts arose from the inversion of Middle Cambrian normal faults. Despite these faults were rotated in the Ordovician during the Sardic Phase, their attitude remains suitable to be reactivated as back-thrust in Variscan times.

Our study highlights how a complex inherited structural setting strongly influence the fold-and-thrust belts style, mainly for what concerns the distribution, geometry and kinematics of the structures.

Tectono-stratigraphic evolution of the external zones of a thrust belt, case of study: the oriental segment of the Maghrebide Chain (NE Algeria)

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Keywords: Tectonic, propagation folds, strike-slip, Miocene

This study relates to a sector located at the southern fringe of the external zones of the Maghrebide Chain of eastern Algeria, on the meridian of Aures. The detailed analysis of certain sectors offering good observation conditions, shows that the overlaps cut the southern flanks of the folds formed previously, during the atlas phase, and engage in these flanks by stretching them. The final geometry of these plicative structures recalls that of the propagation folds which seem, with the overlaps, intimately linked to the strike-slip observed.

All the structural and sedimentary analyzes undertaken as part of this work have made it possible to obtain new results specifying or modifying the results obtained by our predecessors.

It has been possible to show that the folds and associated faults probably formed above basement structures reactivated in a transpressive regime during alpine compression of the Miocene age.

Tectonic Evolution of the Prøven Igneous Complex within the Rinkian Fold-Thrust Belt, West Greenland: Investigation using 3D Photogrammetry

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The amalgamation of cratons and subduction of oceanic lithosphere in the Paleoproterozoic has formed linear orogenic belts worldwide, such as the little studied Rinkian fold-thrust belt on the west coast of Greenland. The Rinkian comprises a Paleoproterozoic shelf sequence formed on the margin of the Rae craton that was deformed by basement-core nappes in a high-grade deformation event at c. 1.82Ga. The northern part of the area affected by the Rinkian fold-thrust belt includes the Prøven Igneous Complex (PIC), a ca. 90 x 80 km large intrusive complex of orthopyroxene-bearing monzogranite to quartz monzonite, which was intruded between ca 1.87-1.9 Ga. The PIC was previously considered to be a syntectonic intrusion, so new work on the structural evolution is important. Here we use detailed photogrammetric mapping on 3D Stereo Blend at the GEUS Photogeological Laboratory in Copenhagen, combined with previous survey work, to identify the major deformation phases of the PIC and their associated structures. We found that the PIC formed as a large sheet intrusion which has been deformed by a westward facing thrust series, developing type II interference fold patterns. This is especially prevalent at the base PIC-metasediment contact, where incompetent rock – partially molten paragneisses and leucogranites – have produced more intense deformation. Furthermore, within the main PIC competent body a type I interference fold pattern has developed between large scale perpendicular folds. Our results demonstrate that the PIC was likely emplaced in situ at shallow crustal levels, and then deformed by the Rinkian orogenic belt. This study has provided new insights into the deformation history of the Prøven Igneous Complex and the tectonic setting for the Rinkian fold-thrust belt overall. Furthermore, the project shows how remote mapping through photogrammetry can cover large areas in revealing detail.

Investigating displacement-distance relationships for fold-thrust geometries using coalmine datasets: Ruhr sub-basin, Germany

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Faults generally show systematic variations in displacement approaching their tips. These variations can be displayed on displacement-distance diagrams - where offset between multiple pairs of footwall and hanging-wall cut-offs are cross-plotted against a distance measured along the fault surface from a reference point. Here we analyse relationships between displacement and distance along thrust faults that cut multi-layered sandstones, siltstones and coals using a mine dataset in the lower Rhine basin - Ruhr sub-basin, Germany. Ideally, Displacement-distance profiles for single isolated faults show diminishing offsets to fault tip-line. Our results are more complex, with varying fault slip gradients that deviate from the idealised bell pattern. These include Trapezoid, Right Triangle, Positively Skewed, Negatively Skewed, Semi-circle and Overlap shapes. A constant displacement–distance pattern is related to sandstone layers. While a variable displacement–distance pattern is correlative with the finer-grained units. Thinly interbedded successions display the most complex displacement-distance relationships. Collectively, these fold-thrust displacement profiles analyses show that the mechanical stratigraphy can influence fault slip patterns, presumably because there are additional strain components that are heterogeneously developed, depending on rock type.

Faulting in the volcano-tectonic collapses: new insights for a coherent evolutionary model

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Keywords: Collapse faults, fault zone evolution, throw analysis, structural survey, Campi Flegrei

Collapse processes in volcanic areas are related to magma migration at depth and/or magmatic chamber emptying. One of the most disruptive phenomena in volcanic areas is represented by the caldera formation. In the last decade, several numerical and analogue models reproduced the collapse process to better constraint the faulting evolution and the deformation mechanisms. These experiments show that a complex fault array accommodates the increasing subsidence of the collapsing block, which is concentric in map view and associated with reverse and normal fault segments in cross-section. Moreover, different studies point out that the fault pattern is influenced by the amount of subsidence, the magmatic chamber morphology, and the host rock mechanical stratigraphy.

However, there is a discussion in the literature about the genetic relationships between normal and reverse faults and the fault array evolution during the increasing subsidence of the collapsing block. Hence, this work aims to characterize a collapse fault array, for the first time using field data, highlighting the kinematic and geometric relationships between fault segments. The exposed faults are located in the pyroclastic deposits of the Astroni eruption in the Campi Flegrei caldera (Italy) and are interpreted to have developed to accommodate the collapse induced by magmatic activity at depth in recent times. The field structural analysis focused on defining the spatial and temporal relationships between the normal and reverse fault segments of the fault array. This analysis was realized using a multi-methodological approach based on (i) the geometrical relationships between fault segments with apposite kinematics, (ii) the angular relationships between fault segments and bedding, and the most important (iii) the throw distribution. We present the preliminary results suggesting that normal and reverse faults developed simultaneously to accommodate the subsidence of the collapsing block, in agreement with the coherent fault model (Walsh et al., 2003). This new evolutionary scenario for collapse faults could be of significance for a better understanding of the strain localization mechanisms and processes within the volcano-tectonic caldera evolution and represent an important tool for mitigating risk connected with geohazard.

Looking for time constraints on fault reactivation in Picos de Europa (NW Spain)

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Keywords: Fault reactivation, Cantabrian Mountains, Zn-Pb ore deposits, Pb isotopes, brecciation.

The Picos de Europa (PE) limestone massif is mainly constituted by Carboniferous units formed in the foreland of the Variscan orogen in NW Spain, and records deformation since the latest stages of the tectonic Variscan cycle. The area became incorporated into an imbricate thrust system emplaced towards the South in the latest Pennsylvanian, when the development of the Cantabrian Orocline modified the configuration of earlier Variscan thrust nappes. During the Permian and Mesozoic, the area was affected by extensional deformation related to the opening of the Bay of Biscay, with the development of the Basque-Cantabrian Basin to the East from the study area and minor basins in the PE Region, where remnants of the Permian-Mesozoic cover are scarce. Subsequent Alpine N-S compression overprinted earlier deformation in this region, giving rise to the Cantabrian Mountains.

Analysing the kinematic history of the long-lived fault systems in the PE area is hindered by the lithological homogeneity of its largely massive Carboniferous limestones, and the paucity of Mesozoic to Cenozoic rocks. However, the relative timing of fault activity can be deduced from the relationship between tectonic deformation and Mississippi-Valley type Zn-Pb ore deposits in the area. The Pb isotopic signature in galena samples from the PE allows their comparison with similar deposits in the Basque-Cantabrian Basin, of Lower Cretaceous age (Velasco *et al*., 1996). Based on the Pb signature, a similar crustal source is inferred for the Pb in the ores in the PE massif and the Basque-Cantabrian Basin, which suggests they formed at roughly the same age.

The spatial correlation between Zn-Pb deposits and hectometre-kilometre-scale fault systems suggests that these structures already existed at the time of ore precipitation and conditioned the mineralising fluids pathways, supporting a relatively old origin for such faults, whose first activity period is generally ascribed to the Variscan Orogeny. In this preliminary study, ores are inspected at outcrop, slab, thin section and scanning electron microscope scales to determine whether they are involved in fault damage zone deformation: discrimination between ore-related hydrothermal brecciation and later tectonic reworking is often necessary. This procedure in combination with fault kinematic data has allowed casting some time constraints on the last activity record of the San Carlos Fault, a kilometre-scale NW-SE sub-vertical fault with Zn-Pb ores in its damage zone. This fault system is now interpreted as having accommodated a last dextral displacement after the Lower Cretaceous, in the context of the Alpine compression.

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Post-orogenic Neoproterozoic stretching across the Indo-Australia-Antarctica amalgam: reviewing the Rodinia supercontinent reconstruction

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The position of India in the Rodinia supercontinent till date is a topic of dispute. While earlier studies prefer to consider India as a part of Rodinia, recent studies suggest isolation of India from Rodinia throughout the Neoproterozoic. The present study demonstrates Neoproterozoic extension from the Eastern Ghats Province (EGP), India and investigates its global significance on the basis of a holistic approach involving structure, metamorphism and geochronology.

The EGP is believed to have formed due to an Indo-Antarctic collision at around 1 Ga. Recently, Pan-African and compression are also being increasingly reported from the EGP as well as Antarctica which raises uncertainty on the timing of the collision between India and Antarctica. Within the EGP, the earliest gneissic segregation (S1) was folded tightly to isoclinally (D2) with the development of an axial planar foliation (S2). The S1/S2 composite foliation is defined by alternate garnet-sillimanite rich and quartz-feldspathic layers in the metapelites and alternate garnet-orthopyroxene rich and quartz-feldspathic layers in the charnockites. Parallelism of melt layers with S1 as well as the occurrence of (001) tilt walls in sillimanites and diffusion creep between feldspar and quartz suggests melting and deformation temperatures at upper amphibolite to granulite facies conditions. The S1/S2 composite foliation was transposed and reoriented from NNE-SSW through E-W to a WNW-ESE striking orientation with the development of the S3 foliation. A prominent down-dip stretching lineation occurs on the northerly as well as southerly dipping S3 foliation surface. The D3 shear zone extends for about a few tens of kilometers across strike and is typically associated with top-to-the-north shear sense along northerly dipping southern boundary and top-to-the-south shear sense along the southerly dipping northern boundary. This indicates extension or stretching across the EGP, following the 1Ga collision. Breakdown of garnet to cordierite in the metapelites have been speculated as a manifestation of decompression during extension (D3). The S3 foliation is defined by alternate segregation of feldspathic and quartz-rich layers and detailed microstructural studies reveal that D3 deformation occurred under middle amphibolite facies conditions at temperatures not exceeding 600 °C. Timing of the D3 deformation has been inferred to have occurred in between 730-680 Ma based on texturally constrained monazite spot ages. Intra-cratonic sag basin has been reported to have formed at around 700 Ma from the Marwar craton of Western India. These basins have been correlated with the breakup of the Rodinia supercontinent.

Similar horst-graben structures ageing in between 900-550 Ma have been reported from the Ruker terrane of east Antarctica. In the adjacent Rayner Province, deformation, metamorphism and fluid infiltration is inferred to have occurred during 100-900 Ma while 800 to 700 Ma ages are being increasingly reported. Importantly Neoproterozoic rifting, magmatism and sedimentation has been documented from Tasmania, south-eastern Australia. Mid-Neoproterozoic extension, documented from widely separated areas of western India to south-eastern Australia is very similar in timing with break-up of Rodinia supercontinent. Therefore, the Neoproterozoic reconstruction of Rodinia can be reviewed in the light of this inter-continental post-orogenic stretching event.

Morpho-stratigraphic evolution of an offshore portion of the Hyblean plateau eastern flank

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Keywords: Trasgressive deposits, Hyblean plateau, Multibeam, seismic stratigraphy

Transgressive deposits accumulate with rising relative sea-level during the landward migration of a coastline and can be recognised through the evidence of a gradual or irregular landward shift of facies, or a deepening of facies that culminates in a surface of maximum flooding.

The offshore area of Marzamemi (SR, Sicily), in the south-eastern portion of the Hyblean foreland, represents an excellent site where to study the development of these deposits and their connection with the sea-level changes. From a geomorphological point of view, the study area is part of the Pantani area, a coastal stretch characterized by a series of lagoons, elongated parallel to the actual coastline and separated by the open sea by elevated ridges of Tyrrhenian calcarenites and by coastal sand barriers.

Through the interpretation of new morphological data (MBES) and the comparison with high-resolution seismic profiles (SPARKER), we have reconstructed the development of deposits connected to the Transgressive System Tract and Highstand System Tract of the last eustatic cycle.

Along the northern sector, the morpho-seismic-stratigraphic analysis highlights the development of three lagoonal systems (L1, L2 and L3) that mark important steps of Late Quaternary sea-level rising.

The deepest lagoon L1 is bounded to the west by the contour -45 m, which identifies a cuspited high paleo-coastline constituted by the outcropping Tyrrhenian substratum (Calcarenites of Marzamemi), only locally covered with highstand deposits. Southwards, the L1 is characterized by a smooth morphology interpreted as beach deposits, while in the central portion a system of tidal bars and channels is widespread and well-imaged in the seismic profiles. Westwards, the lagoon L2 marks a second step of the recent sea-level rising, with the development of a paleo-coastline in correspondence of the contour -35 m. The L2 shows morphological features similar to the L1, with the presence of wide beach deposits to the south and two cliffs that delimited L2 to the west and to the east. Finally, the contour -20 m marks the third significant step of the sea-level rising, and is associated with the paleo-coastline bounding to the west the lagoon L3. The latter hosts within two islets and is confined to the east and west by high cliffs made up by the calcarenite substratum. Only to the south display smooth morphologies attributable to beach deposits. Furthermore, within L3 is present a wide delta oriented west-east and characterized by an irregular trend due to the presence of numerous distributary channels.

Along the southern sector, the morphological features are significantly different, and no lagoon systems are observed, probably due to various inherited morphologies of the paleo-coastlines. Here the outcropping calcarenite substratum is affected by the development of meandering paleo-rivers and karst structures, such as numerous depressions (poljes), commonly developed along the Mediterranean karst regions.

Cyclic brittle-ductile behaviour recorded in high-pressure continental units of the Northern Apennines and deep episodic tremor and slow slip events

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

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

We have studied a well exposed section in the Monticiano-Roccastrada Unit of the Mid Tuscan Ridge where a mesoscopic (~20 m length and 5 m high) compressional duplex deforms the Palaeozoic-Triassic quartz-rich metasandstones, metaconglomerates and minor metapelites with a top-to-the-NE sense of shear (Casini et al., 2007).

Field observations reveal severe strain partitioning within the duplex between metapelite levels, corresponding to 10-50 cm thick high-strain zones, and metasandstone levels, which form relatively strain-free metric horses. Dilational shear veins occur in both lithologies and are composed of iso-oriented quartz and Mg-carpholite fibres and K-white mica marking the stretching lineation. The mylonitic foliation in the metapelites is defined by quartz, chloritoid, pyrophyllite and K-white mica forming a stretching lineation coherent with the one visible in the veins. Geometrical, cross-cutting and petrographic relations suggest that there has occurred cyclic deformation between brittle and viscous conditions, with the veins forming broadly syn-mylonitic shearing. Thermodynamic modeling results suggest >0.8 GPa and 350-400° C for the formation of both veins and the mylonitic foliation.

Dilational shear veins developed in subducted (meta)sediments are a key indicator of episodic tremors and slip events (e.g. Fagereng et al., 2011). We propose that these structures reflect the repeated alternation of localised brittle failure, with dilational shear veins development, and more diffuse viscous deformation. These cycles were probably related to the fluctuation of pore pressure that repeatedly reached lithostatic values. Concluding, these structures can be considered the geological record of episodic tremors and slip events occurring at >30 km of depth in the Apenninic subduction channel.

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Building an orogen-scale database of giant quartz veins: the GIVEPY (Giant Quartz Veins of the Pyrenees) database

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Quartz veins are ubiquitous in orogenic settings, within zones of intense deformation such as faults and fractures in the upper (brittle) crust and shear zones in the lower (ductile) crust. The dimensions of quartz veins can vary dramatically within the same tectonic setting, from millimetric to hectometric thicknesses and from metric to kilometric lengths. However, despite their ubiquity, there are still many open questions about the formation mechanisms of the largest veins, also known as "Giant" Quartz Veins (GQVs). As GQVs are visible in satellite and photogrammetric imagery, they can be analysed by remote sensing mapping and other computer-assisted methods. Worldwide, geological and geographical surveys and institutions offer a wide range of georeferenced geological information, often freely available and regularly updated, which includes high-resolution orthophotography, 3D photogrammetry, satellite imagery and detailed vector-format geological maps. These open access datasets can thus be used to statistically analyse the occurrence, orientation, distribution and host rock variability of GQVs, comparing them to other geological structures (i.e., shear zones, fractures and faults) to gain new insights into the structural controls on vein emplacement at the large scale.

We present a systematic workflow for characterizing GQVs from a GIS-based approach, using the Pyrenees as a natural laboratory. This fold and thrust belt represents an excellent environment for the study of GQVs, specially from a remote sensing approach, due to the large datasets provided by the French (BRGM), Spanish (IGME) and Catalan (ICGC) geological surveys. Geological and geographical information have been used to obtain the main attributes of hundreds of GQVs in the Pyrenees, and the final product is presented as a dynamic database: the GIVEPY (GIant quartz VEins of the PYrenees) database. It includes the shape, coordinates, regional setting, outcropping area, trace azimuth and descriptions of host rock/s (lithology, age and type) of each indexed GQV, representing a macrostructural approach of their orientation and distribution along the chain that can be replicated in other tectonic settings or with other geological structures, such as regional faults, folds, fractures or shear zones.

Preliminary results indicate that the GQVs of the Pyrenees are hosted either in late Neoproterozoic to Carboniferous metasedimentary rocks, Variscan gneisses, late-Variscan granitoids and Mesozoic to Cenozoic sedimentary rocks. Veins mainly consist of discontinuous massive quartz bodies SE-NW to SW-NE oriented and are mostly arranged in the central sector of the Eastern Pyrenees (Canigó and Roc de Frausa Massifs). They are frequently emplaced alongside other regional structural features, such as thrust faults and shear zones of different age. The largest veins (15 km length) are located in the Canigó Massif, although other hectometric to kilometric quartz bodies are also ubiquitous along the chain, from its eastern end in Cap de Creus Massif to its western termination in the Basque Massifs.

Structural Analysis of Mississippian (Tournaisian- Visean) Carbonates in Northeastern Oklahoma

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Carbonate rocks are known for acting as complex fluid conduits due to their heterogenous nature in terms of origin, evolution, and geometry. For decades, it has been recognized that characterizing structures in carbonate rocks is crucial for the subsurface study of hydrocarbons and the characterization of water flow in aquifers. Despite this, the fracture network in Mississippian-aged limestone facies and other lithologies in northeastern Oklahoma have not been completely understood. In this study, we examine structures such as bedding planes, dissolution surfaces, joints, and faults within the lithologies of the well-exposed Mississippian outcrops in Mayes County, Oklahoma, as pathways for fluid.

We conducted photogrammetric surveys from an uncrewed aerial vehicle to create digital elevation models and orthomosaics from high-resolution topographic data. These were used in a GIS as base maps for the mapping of the geology and structures of the study areas. We collected geological and structural data from outcrops during fieldwork.

The Keokuk and Reeds Spring formations outcrop in the study area. Within the Reeds Spring Fm., we find segmented and systematic joint sets that cut through limestone and chert beds, non-systematic joints perpendicular to the bedding surface in chert, dissolution features in 1 limestone, calcite veins, and joints along the bedding planes. On average, large joints are 22 m long with an aperture of 0.13 m, while smaller joints are 1.14 m long. Both strike NE-SW, and dip NW. The small joints spacing ranges from 3.1— 4.7 joints per m. The same types of structures are found in the Keokuk Fm. but are not as widespread throughout. The joints found in the Keokuk Fm. strike N— S and dip west. Normal faults, thrust faults, and joints related to the Seneca Fault also cut the Keokuk and Reeds Spring formations. Normal faults 12— 60 m in length in the Keokuk Fm. strike NE—SW and dip NW in places, while they also strike NW—SE and dip S—SW in others. The dissolution surfaces occur along bedding planes and are up to 2 m wide. We hypothesize that the joints along the bedding planes, the fractured chert beds, the systematic joint sets, and the dissolution surfaces contribute the most to the permeability of the rocks. These structures intersect at high angles to form a fracture network that allows for fluid passage.

Thermal history of the Hikurangi Subduction Margin, New Zealand

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Keywords: thermochronology, apatite, IODP, Expedition 375.

The Hikurangi Subduction Margin, a region that is known to host both shallow slow slip and tsunamigenic earthquakes, accommodates the oblique subduction of the Pacific Plate beneath the Australian Plate on east side of the North Island of New Zealand. Site U1518 of International Ocean Discovery Program (IODP) Expedition 375 (Hikurangi Subduction Margin Observatory) penetrated approximately 500 m of Pleistocene sediments (silt and clay), mud- and siltstones, and turbidites in the outer accretionary wedge, near the deformation front of the Hikurangi Subduction Margin. The top of a splay fault zone, the Pāpaku fault, was penetrated at ca. 300 mbsf, followed by an approximately 60 m thick zone of variable deformation intensity that shows both brittle and ductile deformation features. In order to determine the time and duration of thermal events in the region associated with the fault zone structures of the Hikurangi Subduction Zone, low temperature thermochronology (apatite fission-track and U-Th/He) was applied in 9 samples of silt and siltstones from Site U1518. The hanging-wall samples record the onset of deformation and the generation of thrust faults during the early Miocene (ca. 22 Ma), which occurred after the onset of the subduction. Footwall samples record the age of the Hikurangi Plateau (early Cretaceous).

Interaction between Early Permian low angle normal fault and hydrothermal activity in the central Southern Alps (N Italy)

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Keywords: Permian tectonics - hydrothermal event - structural control - U ore deposit

The development of intracontinental basins at the Europe-Adria boundary is the result of several episodes of crustal thinning occurring along the Variscan orogen starting from the late Carboniferous. In this period, a megashear zone with dextral kinematics led to the transition from Pangea A to Pangea B configuration. Some of these basins are now-day preserved in the central Southern Alps (cSA, N Italy), but during the later Alpine compression, the favourably oriented Permian normal faults have been frequently reactivated and inverted as S-verging thrusts. Along the northern border of the Permian Orobic Basin some Permian structures still preserve their original features, since they exceptionally escaped the Alpine deformation (Zanchi et al., 2019). They are Low-Angle Normal Faults (LANFs) mainly developed at the Variscan basement-sedimentary cover interface and some fragments of LANF are exposed at the head of the Brembana Valley (BG), where the fault zone is characterized by cataclastic bands sealed by centimetric layers of dark aphanitic tourmalinites (Zanchi et al., 2019) and locally by U mineralizations. The precipitation of tourmaline derives from rich in B fluids channelled along high permeability fault zones and the fluids circulation is of regional importance since tourmalinites are associated to further exposures of Permian LANFs in other sectors of the cSA.

Microcrystalline tourmalinitic breccias cutting the basement have been studied from the mineralogical point of view close to the Trompia Valley area (De Capitani et al., 1999), where intrusive bodies of 285 Ma occur. Whole rock analyses were performed both on tourmalinites and granitoids of this area, which look geochemically related, demonstrating that the rich in B fluids are a product of the Permian magmatism.

Tourmalinites genesis has been related to the U mineralization of Novazza-Vedello district by several authors (De Capitani et al., 1999), even though this correlation is not clearly demonstrated so far. Low U concentration was detected with bulk analysis of tourmalinites from different sectors of cSA, however new observations on rocks nearby the U mineralization district indicate the presence of tourmaline crystals combined with minerals likely relatable to the metallogenic event. Our main goal is providing a better characterization of the regional hydrothermal event and to relate it with the structural setting, which influenced the fluids circulation in this intracontinental extensional configuration.

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Defining subsidence histories on former Tethyan rifted margins: examples from the western Alps and Sicily

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Keywords: Backstripping, Subsidence, Tectonics, Alps, Sicily

During the Mesozoic, the relative movement of Africa and Eurasia plates charts the opening of the Tethys Ocean. The rifting phase is well established by the stratigraphic sequences of Western Alps and Apenninic-Maghrebian Chain, which provide exceptional records of continental margin evolution and basin subsidence. The Briançonnais domain (western Alps) is pivotal for testing various rifting models. It contains a remarkably uniform succession of very shallow-water carbonates of Triassic age, capped by Middle-Jurassic shallow-water carbonates or by non-deposition before passing abruptly up into deep-water facies (Lemoine et al., 1986; de Graciansky et al., 2010). The Mesozoic succession of Mt Judica (Sicily) starts with Carnian clays and silty clays containing ammonites, followed by upper Triassic pelagic cherty limestones and Jurassic-lower Cretaceous radiolarian cherts containing intercalations of basic volcanic rocks (Carbone et al., 1990). Backstripping the Mesozoic sequences of the western Alps informs models of continental lithospheric stretching of the Tethyan margin, while the sedimentary record of Mt Judica is a tangible record of the deep Ionian basin formation (Speranza et al., 2003). Although stratigraphic sequences are particularly suitable for being tested by uniform stretching models, both examples have common issues. We quantify Meso-Cenozoic subsidence histories through 1D Airy correction backstripping method, estimating various scenarios based on different plausible eustatic sea level changes and bathymetry. Both, indeed, show substantial subsidence, especially in the Jurassic, which is represented not by enhanced thicknesses of strata but by increases in palaeobathymetry. Therefore, demonstrating the history of rifting is critically dependent on these estimates – a key uncertainty for determining stretching factors. Estimating palaeobathymetry and its variation through time is challenging to establish not only the finite stretching factors but also but also if rifting has been polyphase through the Mesozoic.

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Evidence of intricate finite strain pattern in the external sector of collisional belts: the case of Marguareis Massif (southwestern Alps)

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Keywords: Marguareis Massif, shallow tectonics, continental units, southwestern Alps

In the Margaureis Massif, located between Maritime and Ligurian Alps along the Italian-French border, we document a stack of low- to very low-grade Helminthoid Flysch Unit sandwiched between Briançonnais Units stemming from the Europe continental margin. Helminthoid Flysch Unit consists of a Late Cretaceous sedimentary succession detached from its original basement. Briançonnais Units, instead, show a typical continental succession regarded as the witnesses of sedimentary deposits upon fragments of the Europe margin progressively involved in the alpine collision starting at middle Eocene.

To unravel the complex structural architecture of the area we performed a multidisciplinary approach including geological mapping and micro- to map-scale structural analysis.

The units, from the today highest to the lowest structural levels, are: the Marguareis Unit (MU, Briançonnais Domain), Helminthoid Flysch Unit (FH) tectonically overlaying onto the Cima del Becco Slice and Cabanaira Unit (BS and CU respectively, Briançonnais Domain). FH consists of basin plain deposits passing upward to deep-sea fan coarse-grained turbidite. MU, BS and CU show Meso-Cenozoic sedimentary sequences showing a transition from Triassic-Jurassic carbonates into middle Eocene siliciclastic turbidites.

Each tectonic unit recorded pre-, syn- and post-stacking deformation events (Sanità et al., 2020). FH recorded two pre-stacking deformation events ($D1_{FH}$, $D2_{FH}$). $D1_{FH}$ is testified by $S1_{FH}$ slaty cleavage. $D2_{FH}$ phase produced a markedly differentiated $S2_{FH}$ crenulation cleavage and related southwestward-vergent $F2_{FH}$ folds. Marguareis Unit recorded two pre-stacking deformation events ($D1_{MU}$, $D2_{MU}$). $D1_{MU}$ is represented by a pervasive $S1_{MU}$ foliation (slaty cleavage) associated to southwestward-vergent isoclinal $F1_{MU}$ fold systems. $D2_{MU}$ phase produced a $S2_{MU}$ crenulation cleavage and related northeastward-vergent $F2_{MU}$ fold systems. The Cima del Becco slice shows structural features similar to those depicted in Marguareis Unit. Cabanaira Unit recorded one pre-stacking deformation event ($D1_{CU}$) testified by the $S1_{CU}$ slaty cleavage associated to southwestward-vergent $F1_{CU}$ fold system. The syn-stacking events are testified by unit-bounding shear zones with SW sense of movement and the km-scale $F3_{MU}$ fold ($D3_{MU}$) developed in the Marguareis Unit only and associated to its thrusting onto Helminthoid Flysch. The whole stack, after the Late Eocene-Early Oligocene syn-stacking events, recorded the same post-stacking deformation history represented by a post-stacking fold system with sub-horizontal axial plane and fault system. Similar tectonic evolution was documented in others sector of the Western Alps.

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The Ferriere-Mollières Shear Zone (Argentera Massif, Western Alps): an example of a regional-scale type II shear zone in continental crust

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Keywords: Argentera Massif, Ferriere-Mollières Shear Zone, mylonites, transpression, strain softening shear zone

In the Western Alps a NW-SE steeply dipping km-scale shear zone (the Ferriere-Mollières Shear Zone, FMSZ) cross-cuts Variscan migmatites in the Argentera External Crystalline Massif. Geological mapping revealed an increasing deformation gradient toward the center of the shear zone: the external part of the FMSZ is characterized by the presence of high-grade protomylonites while, moving toward the center, medium-grade mylonites and subsequently lower-grade ultramylonites occur (Carosi et al., 2016).

Simonetti et al. (2018) recognized that the FMSZ evolved under decreasing temperature conditions. This is also confirmed by temperature values obtained with the opening angle thermometer of quartz c-axis applied on sheared rocks in different position within the shear zone. The study of kinematics of the flow, performed with several independent vorticity gauges, revealed that the deformation regime progressively changes along the deformation gradient from a pure shear-dominated transpression to a simple shear dominated transpression. In particular the amount of simple shear increases towards the center of the shear zone from ~24 % in the protomylonites to ~62 % in the ultramylonites. U-Th-Pb monazite petrochronology highlights an older deformation age in the protomylonites (~340-330 Ma) compared to the most sheared rocks (~320 Ma).

The presence of medium- to high-grade metamorphic mylonites associated with lower-grade ones, localized in the central part of the FMSZ, the strong deformation gradient and the changes in the deformation regime and age of deformation along the gradient are evidences that the FMSZ evolved as a type II shear zone (Fossen, 2016). Here deformation localizes in the central part because of strain softening induced by fluid circulation. Thus, the margins become inactive and preserve the features acquired during the early stages of shearing while the active part gets progressively thinner and records the final stages of shearing.

According to this model at least three main stages of development can be recognized, each one characterized by specific age, deformation temperature and deformation regime.

The FMSZ should be considered as a new example of a strain-softening regional-scale shear zone that can be useful for future process-oriented investigations.

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Clastic injections and intrusion fracturing in the basal shear zone of the Esla Nappe (Cantabrian Zone, NW Iberia): flow regime estimation and temperature constraints

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Keywords: Sand injection, Thrust-related deformation, Fault rocks, Clumped isotopes, Cantabrian Zone

The Esla Nappe is located in the foreland fold-and-thrust-belt of the Variscan Orogen in the NW Iberian Massif (Cantabrian Zone). The nappe was emplaced during the Moscovian, with a minimum thickness of *ca.* 4 km and a displacement in the order of 19 km (Alonso, 1987). Its thin basal shear zone (ENSZ, *ca.* 2-3 m thick) records a variety of deformation processes that alternated throughout its emplacement, including cataclastic flow, pressure solution, and hydrofracturing with related calcite vein precipitation (de Paz-Álvarez *et al.*, 2021).

In the late emplacement stage, the ENSZ was affected by intrusion fracturing (Arboleya, 1989; de Paz-Álvarez *et al.*, 2021). The base of the nappe was brecciated, and previous anisotropies such as bedding planes, joints and stylolites were re-opened and injected with a slurry composed of overpressured fluid, quartz-sand grains sourced from the footwall and host-derived fragments. Locally, the interconnected network of clastic dykes and sills reach 20 m over the base of the ENSZ. The injected material was subsequently cemented with fine-grained calcite locally fragmented. Dyke orientation analysis suggests that the injection process took place in relation with the achievement of large fluid overpressure conditions in the footwall, in excess of lithostatic values (> *ca.* 110 MPa). Progressive fluid accumulation in the footwall and a change in the stress regime at the ENSZ favoured the breaching process.

Flow conditions calculation based on terminal fall velocities of the particle array suggests that the thickest injections (*ca.* 1 m thick) required transitional to turbulent flows (Reynolds (Re) $< 1.2\times10^4$) and velocities in excess of 35 cm/s. The thinner ones (*ca.* 1 cm) were characterised by laminar flow (Re < 800) and variable velocities in the order of 1–35 cm/s. Flow velocity and Re for the thick injections are larger than previous estimations for deep injections, where vertical pressure gradients are limited. Our results suggest that turbulent flow, albeit with modest Re values, was achieved at 4 km depth in the Esla Nappe.

Clumped isotope geochemistry has been used to estimate the temperature of calcite cement precipitation of the injections, which varies between 71 and 86 °C, with an average of 80 ± 4 °C. Calcite stable isotope ratios are within the range of host-rock values ($\delta^{13}C$ = -0.15, $\delta^{18}O$ = -9.53). This suggests that fluids were in thermal equilibrium with the host rock, and thus their temperature can be used to estimate the geothermal gradient of the Esla Nappe during Variscan deformation, which was in the order of 17 °C/km. The calculated gradient, very similar to estimations for oceanic trenches, falls in the lower range for current foreland basins.

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Evolution of a major extensional shear zone in the middle crust (Val d'Ossola, Ivrea-Verbano Zone, Western Alps)

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

The deformation processes and rheology of mafic shear zones are the subject of notable debate because their main mineral constituents (e.g., plagioclase, amphibole, clinopyroxene) are expected to be rheologically strong at middle to lower crustal conditions (e.g., Bürgmann & Dresen, 2008). Nevertheless, under specific conditions associated with variations in rock composition/texture, temperature/pressure or under the presence of fluid/melts, even the strong lithologies/minerals can become weak, and reactions can proceed during deformation, becoming itself an important weakening mechanism in rocks (Lee et al., 2020).

In this contribution, we investigate exhumed shear zones developed in the middle crust with the aim to decipher which heterogeneities promoted the strain localisation in a fully ductile regime. To address this issue, we integrate microstructural, geochemical, and petrological data to characterise the evolution of an extensional shear zone of the Ivrea-Verbano Zone (IVZ, Western Alps) exposed along the Ossola Valley, the Anzola shear zone (ASZ). The ASZ has always been the focus of several works (e.g., Brodie, 1981; Altenberger, 1997; St*ü*nitz, 1998) because it gives a great opportunity to study shear localization within amphibolite to granulite facies conditions mafic rocks at middle/lower crustal levels. We performed quantitative orientation analysis (SEM-EBSD) to characterise the rheological behaviour of the mylonites and geochemical analyses (EMPA and LA-ICP-MS), which emphasise that strong heterogeneities occur along the ASZ and respect with the relative wall rocks (gabbroic and felsic/mafic granulite).

Our preliminary results suggest that deformation in the ASZ took place under granulite/amphibolite facies conditions (650-800°C) and that dissolution-precipitation creep is the dominant deformation mechanism. Evidence of synchronous deformation and mineral reactions of clinopyroxene suggests that metabasite become mechanically weak during the general transformation weakening process. This process was driven by melt flux deformation demonstrated by the occurrence of large amphibole porphyroclasts and interstitial ilmenite. Petrographic and textural observations suggest that the ASZ was characterized by melt-rock interaction with the wall rocks. In fact, our results show that the ASZ is extremely heterogeneous consisting by alternation of amphibolitic and calcsilicate layers, supported by the geochemical observations (occurrence of two different composition cpx: diopside and hedenbergite). The possible pre-existing heterogeneity (i.e., layering and grain-size variations) was probably the *loci* of concentrated shear deformation and the magmatic fluids could be the source of clinopyroxene weakness and of the abundant amphibole. With this work we want to emphasize that the combination of multidisciplinary approach may allow to better unravel the kinematics and the evolution of major extensional shear zone in the middle crust.

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Local variations of metamorphic record from compositionally heterogeneous rocks: Inferences on exhumation processes of continental (U)HP–HT unit (Cima di Gagnone, Central Alps)

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

Metamorphic terranes often preserve relicts of variable metamorphic conditions associated with compositionally and rheological heterogeneous rocks. This variability commonly results in small lenses of one rock type characterized by significantly higher pressure (P) and/or temperature (T) conditions than its surrounding host rocks. The well-known Cima di Gagnone area in the Central Alps represents such an example, as relatively small, 1– to 100 s-meter scale, ultrahigh–pressure and high–temperature ultramafic lenses are enveloped within amphibolite–facies metasediments. In this study, new field observations, microstructural and petrological analyses, and thermodynamic modelling results on these metasediments are presented showing that these rocks generally experienced medium pressure and medium temperature conditions of 1.0–1.2 GPa and 640– 700 °C. However, a few samples from the immediate proximity of the ultramafic lenses record significantly higher P–T conditions of 1.3–1.7 GPa and 750–850 °C, approaching the high pressure and high temperature conditions of the ultramafic bodies (1.5–3.1 GPa, 650–850 °C). Mineral/bulk chemistry changes during growth of new mineral phases lead to local melt/fluid interaction between metasediments and ultramafics during the deformation at the HT-HP stage. Preliminary U-Pb LA–ICP–MS dating suggests that zircon grains from the metasomatic reaction zone have been fully re–equilibrated during the early stage of Alpine exhumation (~36 Ma), while the large part of the metasediments records only pre–Alpine ages. We finally discuss these new data into the regional *P–T–t–D* paths and the repercussions of these findings for understanding the exhumation processes of HP rocks. Our work addresses to focus the attention on the significant role of small-scale deformation as driver of local different equilibria that may significantly affect the metamorphic record of orogenic rocks.

Geochronologic and thermobarometric constraints to the opening to closure of the Rocas Verdes Basin, southern Patagonian Andes (52-54°S)

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Keywords: Rocas Verdes Basin; Patagonian Andes; Geochronology; Fold-and-Thrust belt; Metamorphic Petrology

The Late Jurassic-Early Cretaceous Rocas Verdes Basin (RVB) in southernmost Patagonia was a marginal to backarc basin with quasi-oceanic floor originated during the early dispersal of Gondwana landmasses. The closure of the RVB forming the hinterland domain of the Magallanes Fold-and-Thrust Belt (MFTB) marks the beginning of the Andean orogeny in the region, when the Antarctic Peninsula is separated from the continent to the west, and flexural subsidence to the east generated the foreland Magallanes-Austral Basin. We investigate the structural, metamorphic and geochronologic evolution of RVB in the segment between 52-54°S, which connects the N-S oriented southern Patagonian sector with the E-W- oriented Fuegian sector of the MFTB. New detrital zircon U-Pb ages constrain the rift-related volcanism to ca. 160 Ma in metatuffs, and the maximum depositional age of ca. 125 Ma in metapsammopelites, during the opening of the RVB. These rocks are currently imbricated in a 30-km wide NNW-SSE oriented thrust stack, with a mylonitic S_1* foliation verging to the continent (NE). The foliated phengite-chlorite bearing metatuffs record pressure-temperature (P-T) conditions between ~3-6 kbar and ~210-460 °C, consistent with underthrusting of the RVB up to 23 km depth, beneath the parautochthonous magmatic arc in the west (Paiva Muller et al., 2021). A metapsammopelite with hornfels texture partially overprinting the early foliation records 6 kbar and 460°C, and a neighbor underformed quartz-diorite intrusion was dated in ca. 83 Ma (zircon U-Pb), constraining the minimum underthrusting age (Paiva Muller et al., 2021). $^{40}Ar/^{39}Ar$ phengite dates from a mylonitic metapelite range between ca. 73-70 Ma, likely meaning the age of thrusting and backthrusting during the uplift of the underthrusted crustal stack (Paiva Muller et al., 2021). These findings allow relationships between the shear zones within the hinterland of the MFTB, showing that the southern Patagonian sector has a ~ 400 km long mylonite belt of RVB succession underthrusted before the Campanian, correlated with the emplacement of the Sarmiento ophiolites (Calderón et al., 2012). The Fuegian sector share similar minimum underthrusting ages (Klepeis et al., 2010), but the exhumed Paleozoic to Lower Cretaceous rocks or the Cordillera Darwin, metamorphosed at amphibolite facies, reflects a higher magnitude of exhumation to the south of the Estrecho de Magallanes. Tectonic features as the bending of the Patagonian Orocline that started with the RVB closure, the shift to dominant strike-slip shearing during the Cenozoic at the Fuegian Andes, or even a higher degree of erosion due to intense glacial erosion at Cordillera Darwin are amongst the reasons of such differences between the northern and southern sectors of the southernmost Andes.

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Zircon Raman Dating – a new tool to reveal cooling histories

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Keywords: Thermal history, zircon, Raman spectroscopy.

Thermochronological methods are widely used to decipher the thermal history of orogenic belts and sedimentary basins, and determine the rates of tectonic processes. Still, the availability of datable minerals and their closure temperature ranges often limit the applicability of thermochronology. Therefore, the development of new thermochronological tools is necessary. An emerging but not yet established method in the field of thermochronology is zircon Raman dating. It is based on the radiation-damage accumulation of zircon by the α-disintegration of ^{238}U, ^{235}U, and ^{232}Th in the zircon crystal lattice. The changes in the lattice can be traced and quantified through the increase of Raman bandwidths with α-dose. An apparent Raman age is calculated from the ratio of measured damage D and the U and Th concentration. Radiation damage anneals upon heating. Zircon Raman dating thus yields cooling, reset, or mixed ages rather than formation ages, depending on the sample's thermal history. We present first thermochronologic data from a slowly cooled gneiss from the Mogok Belt, Myanmar, to validate the experimentally determined closure temperatures for zircon Raman dating, indicating that this method yields reasonable results for simple cooling histories. We also discuss the detection of partial radiation-damage annealing as a tool to constrain metamorphic peak temperatures in low to medium-T metamorphic rocks.

Recognizing tectono-metamorphic discontinuities in orogenic belts: implications for the Greater Himalaya Sequence assembly and exhumation in NW Himalaya

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Keywords : Himalaya Shear zone; High Himalayan Discontinuity; GHS tectonic and metamorphism; Monazite geochronology; in-sequence shearing

Abrupt modifications of metamorphic, deformation and time path within collisional belts are known as tectono-metamorphic discontinuities. In the Himalaya, within an exhumed mid-crust mega tectonic unit, the Greater Himalayan Sequence (GHS) a tectonic-metamorphic discontinuity called High Himalayan Discontinuity (HHD) has been mapped in the central and eastern portions of the belt. The HHD has never been reported in NW Himalaya. In order to assess the HHD presence in the NW portion of the belt, a multidisciplinary approach comprising fieldwork, microstructural analyses, metamorphic petrology and in situ monazite geochronology was addressed to the GHS in the Alaknanda valley, Garhwal Himalaya (NW India). This applied integrative methodology allowed us to reveal the occurrence of a newly high-temperature ductile shear zone, the Badrinath shear zone (BSZ), within the GHS.

The Badrinath mylonite affects a sillimanite-bearing migmatitic gneiss from the Upper GHS (GHSU) and displays top-to-the-south thrust-sense of shear. Two main stages of BSZ developing were constrained: (1) the pre-mylonitic (Pre-Dm) stage took place during prograde metamorphic path and reached conditions of 700-720°C and 10 kbar during the time interval of 34 and 23 Ma, with incipient partial melting, followed by (2) the mylonitic stage (Dm) in which the BSZ underwent nearly-isothermal decompression triggered by the shear activity between 23-19 Ma, with exhumation rate of ±0.3 cm yr-1. Moreover, the rocks from the BSZ footwall, the lower part of GHS (GHSL) experienced metamorphic conditions of ca. 660-700°C and ca. 10-11 kbar followed by decompression nearly ~3 Ma after the BSZ.

The occurrence of an HT shear zone, the contrast in exhumation onset (ca. 3 Ma) and P-T paths between the GHSL and GHSU, set up a tectono-metamorphic discontinuity inside the GHS in the study area. The BSZ features match with the HHD geological features and represent its prolongation in Garhwal Himalaya, India. The BSZ is the first reported HHD branch in NW Himalaya, corroborating with regional extent of the HHD accomplishing an important role during the GHS exhumation. Such findings support that the deformation was driven by high-temperature shear zones during progressive mid-crust exhumation from top to bottom in the GHS, as highlighted by the model "in-sequence shearing" (Carosi et al., 2018, 2019; Montomoli et al., 2013, 2015).

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Marble mylonites from the South Tibetan Detachment System around the Manaslu Massif (central Himalaya): evidence for a complex rheological evolution of a low-angle normal fault through fabric analysis

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Keywords: Shear zone development, differential stress, calcite crystallographic preferred orientation, drop in kinematic vorticity, South Tibetan Detachment System

The South Tibetan Detachment System (STDS), in Himalaya, is a prime example of syn-collisional extensional shear zone, occurring for over 2400 km along the strike of the belt. A composite architecture of the STDS has been described around the Everest area (Eastern Nepal), where a lower normal ductile- and an upper brittle- branch of the detachment have been recognized (Carosi et al., 1998; Law et al., 2004). In this area, mostly quartz-bearing lithologies are involved within a thick mylonitic zone, related to the ductile STDS activity. However, lithologies affected by the STDS and STDS evolutionary history, vary along strike (Montomoli et al., 2017).

Until now, little work has been done in central Himalaya where marble, with a different rheological behaviour than quartz-dominated rocks, is a widespread lithology. In this contribution, we examine a suite of marbles affected by the STDS around the Manaslu Massif (Western Nepal), comparing the deformation mechanisms recorded by calcite. Calcite microstructures (e.g., grain size and shape, twins) and crystallographic preferred orientations, coupled with petrographic observations, highlighted how different deformation mechanisms of calcite recorded the deformation over time. Particularly, the comparison between grain boundary mobility and twinning pointed out paleo stress, strain rates, temperature and kinematic of the flow variations overtime. Decreasing temperatures from an early-stage of shearing to a late-stage of shearing coexist with increasing differential stress for comparable strain rates. This supports a complex evolution of the STDS, with different thermal, flow and stress regimes occurred during the deformation. We propose a progressive evolution of the STDS towards shallower structural levels, with a non-steady-state deformation (e.g. Fossen and Tikoff, 1997) in which progressively more general shear replaced high-temperature simple shear flow during cooling, strain hardening, and narrowing of the shear zone.

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Structural geological study of two transects (Modi Khola and Mardi Himal) in the Annapurna Range, central – western Nepal (Himalaya)

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Keywords: Himalayan Chain, quartz c-axis fabric, kinematic vorticity analysis, meso and microstructural analysis

Along the Modi Khola and Mardi Himal transects, in the Annapurna Region (central-western Nepal) the main units of the Himalayan range crop out. The studied transects extend for about 20 km in length. From the lower to the upper structural level it is possible to recognize the medium-low grade metamorphic rocks of the Lesser Himalayan Sequence (LHS), the medium- high-grade metamorphic rocks of the Greater Himalayan Sequence (GHS), and the weakly or non-metamorphic rocks of the Tethyan Himalayan Sequence (THS). Two of the main tectonic discontinuities of the Himalayan chain respectively separate these Units: the lower Main Central Thrust Zone (MCTZ) with reverse kinematics and the upper South Tibetan Detachment System (STDS) with normal kinematics. In the study area other discontinuities within the GHS are present: the Bhanuwa Fault (23 – 19 Ma; U – Th – Pb on Mnz e Lu – Hf on Grt; Corrie & Kohn 2011; Shrestha *et al*. 2020), the Sinuwa Thrust (27 – 23 Ma; U – Th – Pb on Mnz and Lu – Hf on Grt; Corrie & Kohn 2011; Shrestha *et al*. 2020) and the Modi Khola Shear Zone (MKSZ; 22.5 – 18.5 Ma; U – Pb on Mnz, Zr and Xtm in deformed leucogranite; Hodges *et al*. 1996). At present day the Bhanuwa Fault and the Sinuwa Thrust were identified only on the base of petrochronological arguments.

Field mapping combined with mesoscale analysis, and detailed microstructural and petrographic description of 62 oriented samples allowed to produce an updated geological map of the study area and a precise description of the main tectonic discontinuities.

On four samples, three related to the MCTZ and one related to the Unit Ia of the Lower GHS (GHSL), the quartz c-axis fabric has been measured manually by using an Universal stage. The obtained pole figures allowed us to infer the sense of shear (top – to – the – S) and deformation temperature. The obtained deformation temperatures are in good agreement with the observed microstructures and are between 525 – 618 ± 50 °C for the MCTZ and of 635 ± 50 °C for the LGHS. The c-axis fabric of the sample collected close to the Bhanuwa Fault, for which the kinematics is still debated, shows an asymmetry pointing a top – to – the – S sense of shear suggesting therefore a thrust sense kinematics.

On three samples, two from the MCTZ and one from the Lower GHS, kinematic vorticity analysis was performed. The results allowed to characterize the deformation regime highlighting the presence of a non-coaxial flow with an important pure shear component (between 60-65%).

Combining the obtained results with the previous literature data it was possible to advance a tectono-kinematic model for the exhumation of the GHS in the study area. Excluding the MKSZ (interpreted as an out-of-sequence thrust), the progressive activation at gradually lower structural levels of the Sinuwa Thrust, the Bhanuwa Fault and the MCTZ is consistent with the in-sequence shearing model that considers a progressive migration of deformation and of the exhumation within the GHS towards the foreland. This model is well documented by other authors for other sectors of the Himalaya (Montomoli *et al*. 2013, 2015; Iaccarino *et al*. 2015, 2017; Carosi *et al*. 2018).

The new data presented in this work, obtained thanks to a multidisciplinary and multiscale approach, significantly contribute to better define the structural and geological asset of the Modi Khola and Mardi Himal area.

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Young Researchers in Structural Geology and Tectonics

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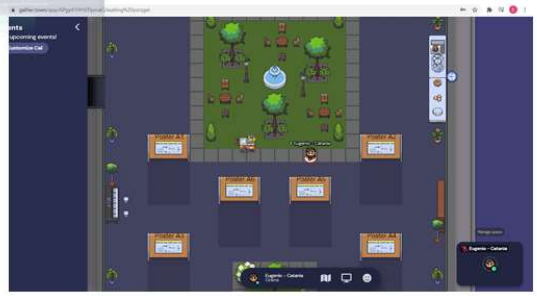

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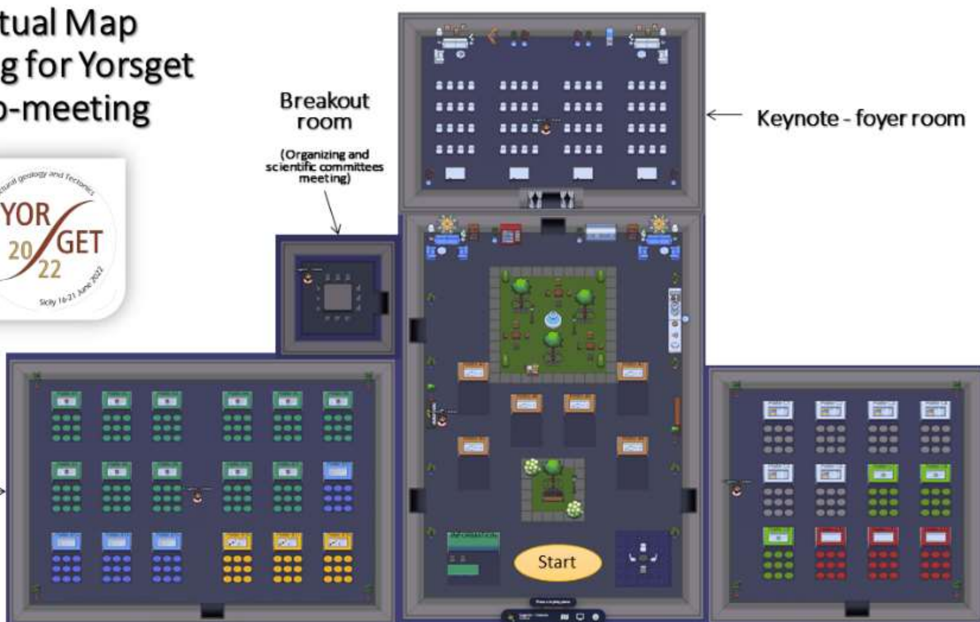

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- ***Mute your microphone when you're not talking.*** *Background noise disrupts the meeting for everyone and might prevent us from hearing the information that we need. Choose a quiet location – away from pets, children, etc. Turn off the TV and any music. There is a mute button on your phone for a reason. The mute button is your friend. Use the mute button when you are not speaking.*
- ***Do not use a speakerphone.*** *They really interfere with the quality of the call. If you are a group participating in the conference, it might make sense. But if it is just you, please don't use a speakerphone.*
- ***Do not multi-task.*** *Stay mentally present. It is easy to get distracted on a conference call. But our objective is important and we need your full attention in order to meet the goals of the meeting. You were invited to this meeting because we believed you had something unique to contribute.*
- ***Identify yourself.*** *Before you start to speak, please state your name so we know who is talking. Everyone might not recognize your voice.*
- ***Speak slowly and clearly.*** *Please try not to talk over another speaker. If there are multiple participants, people tend to talk at the same time – making conversations extremely difficult to understand. Try to speak one at a time so that we can follow your point in its entirety.*
- ***Stick to the agenda.*** *Please try to stay focused. This conference has a specific purpose. Let's stick to it.*
- ***No one-on-one side conversations.*** *All discussion is meant for everyone.*
- ***Ask for clarification.*** *If there is something that you don't understand, please ask for clarification.*
- ***Everyone Must Participate.*** *Be candid. Speak your mind. Everyone in the meeting is expected to share ideas, ask questions, and contribute to the discussions. You must share your perspective and speak honestly.*
- ***Attack the problem, not the person.*** *There will be differences of opinion. You will not agree with everything that is discussed. But please be open to hearing other people's perspectives. If you don't agree, respectfully challenge the idea – not the person. Honest and constructive discussions are needed to obtain the best results.*

Thank you and enjoy the conference !!!

Rosanna, Rob, Rodolfo, and Eugenio