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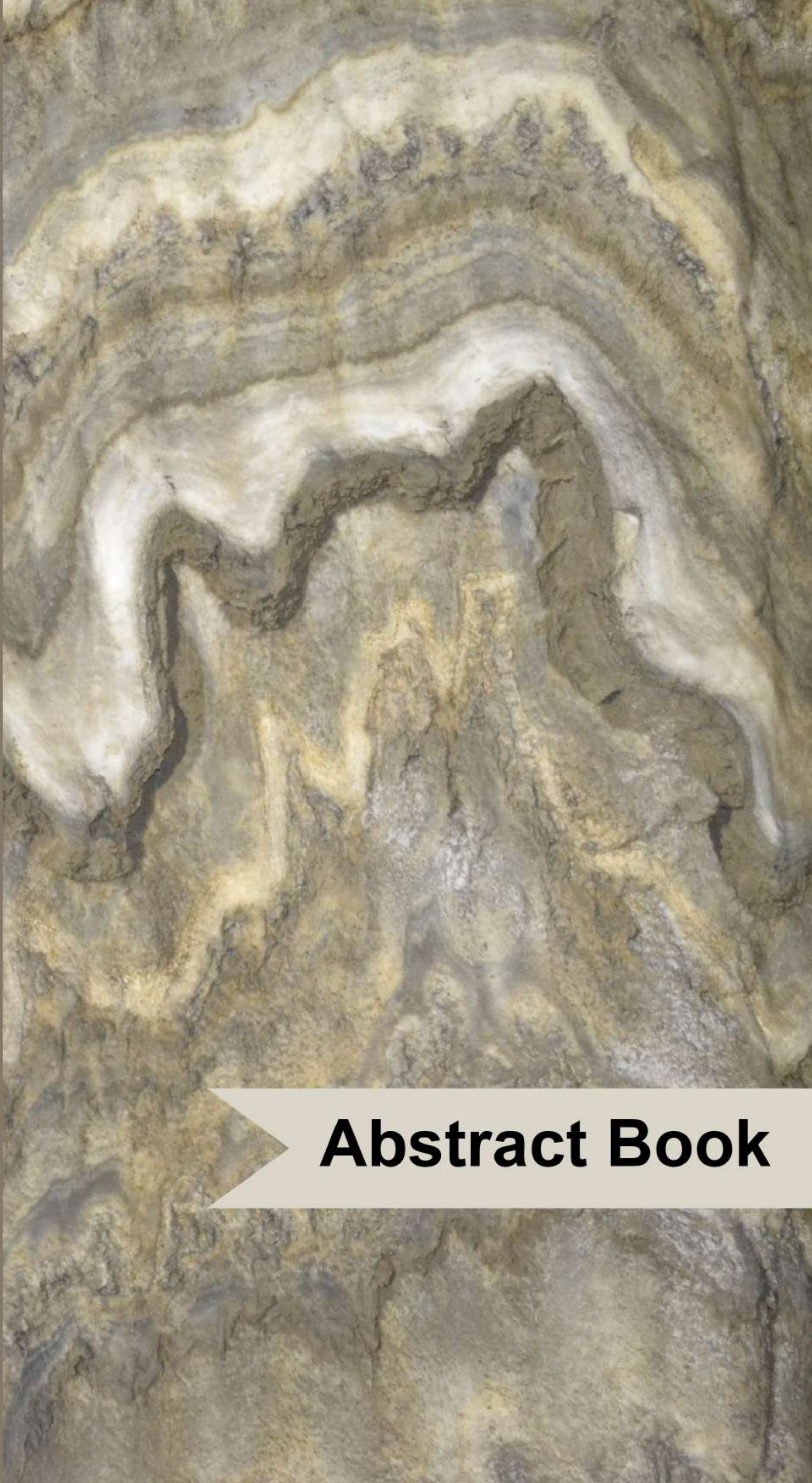

Abstract Book

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Tectonic style and faults kinematics from the Saghro massif (Anti-Atlas, Morocco): Implication on the structural evolution of the West African Craton margin

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Keywords: Structural mapping, faults kinematic, deformation style, Anti-Atlas, West African Craton

The Saghro massif of the Moroccan Anti-Atlas belt is renowned for its tectonic complexity inherited from Pan-African, Variscan, and Alpine orogenic cycles. This makes it an ideal area to investigate the tectonic evolution of the West African Craton northern margin from Precambrian to present times. In this study, remote sensing structural mapping and extensive field observations and measurements have been integrated to decipher the tectonic style and faults kinematic history in the Precambrian-Cambrian and Cenozoic outcrops of the southwestern Saghro massif. The structural analysis shows three fault systems, namely N-S to NNE-SSW, NE-SW to E-W, and NNW-SSE to NW-SE. Extensive and transpressive/compressive tectonics reactivated the NE to ENE major faults, while most of the NW-SE pan-African structures are tectonically aborted. These patterns played a major role in the origin of the present-day reliefs of the Saghro massif. The ‘‘*thin-skinned*’’ deformation style characterizes the Ouarzazate foreland basin, accommodated by deep detachment faults and fault- propagation folds favored by multiple post-variscan incompetent levels. The increased fracture frequency with increasing rock strength and deformation intensity has a significant implication in the faults distribution over the basement and covers outcrops. Undoubtedly, the resulted structural map allows the revision and updating of existing geological maps and helps to understand the tectonic correlations between the southern orogenic border of the High Atlas and the Anti-Atlas fold and thrust belt.

The influence of lithospheric geometry in Andean evolution: an example from the 33-36°S area

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Keywords: Subduction-orogeny, lithosphere-asthenosphere boundary, east-vergent detachments

A current topic of debate in the Southern Andean tectonics is regarding the vergence of the orogenic system, with two end-member models: an east-vergent model and a west-vergent model. The former proposes that the main detachments that accommodate shortening are rooted below the orogen at 10-12 km depth and the different morphotectonic units have been successively uplifted from west to east (Ramos et al., 2004; Farias et al., 2010; Giambiagi et al., 2012). In turn, the west-vergent model interprets that the deformation is accommodated by an east-dipping shear zone rooted in the lower crust beneath the eastern flank of the Andes (Armijo et al., 2010; Riesner et al., 2018, 2019). Furthermore, these models estimate different amount of shortening. At the Aconcagua transect at ~34°S, for example, there is around 70 km shortening calculated in the east-vergent model (Farias et al., 2010; Giambiagi et al., 2012) while 30-50 km are estimated in the west-vergent model (Riesner et al., 2018).

We develop geodynamical models representative of two E-W-transects (33°40'S and 36°S) based on geological and geophysical information about the area. We try to replicate the geometry of the upper plate, with an asymmetric lithosphere-asthenosphere boundary due to subduction corner flow. We split the model domain to west and east parts, where the western part has a thicker lithosphere representing the forearc as a rigid indenter (Farías et al., 2010) than the eastern part in which the lithospheric mantle is eroded thermally by the corner flow.

Results of our models show that the geometry of the lithosphere-asthenosphere boundary is an important factor controlling the orogenic vergence. In particular, a principal east-vergent crustal-scale detachment is formed in both transects, which is in accordance with the east-vergent model (e.g. Ramos et al., 2004; Farias et al., 2010; Giambiagi et al., 2012).

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Stratigraphic control of slip localization and the role of dynamic weakening in the late stages of emplacement of the Moine Thrust Zone, Scotland: Insights from friction experiments

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Keywords: Slip localization; Friction experiment; Frictional strength; Stability parameter; Moine Thrust Zone

Most geodynamic models of orogenic wedges require significant weakening to occur along basal detachments to allow large-scale horizontal shortening. The mechanical weakening that allows major displacements to occur along thrust faults is attributed to the presence of mineralogically weak fault rocks (Collettini et al., 2009), the development of overpressured pore fluids (Hubbert and Rubey, 1959) or other various strain-induced softening mechanisms related to grain-size reduction. In this work, we explore the lithological control over weakening mechanisms - and the potential role played by dynamic weakening - that lead to slip localization in large-scale thrust faults, employing an approach that combines field observations and frictional experiments to examine Cambro-Ordovician rocks of the foreland sequence of the Moine Thrust Zone. The Silurian Moine Thrust Zone, in Scotland, comprises a zone of complex imbrication where the principal fault plane accommodated over 100 km of WNW dip slip motion during the Caledonian orogeny (Elliott and Johnson, 1980, McClay and Coward, 1981). During the late stages of thrust emplacement, the Cambro-Ordovician shallow-marine sediments were involved in an intricated system of imbricates within the structurally lower thrust sheets of the Moine Thrust Zone. Slip localization within the fine-grained clastic units and carbonate-dominated formations has been reported within the imbricates and, generally, credited to frictional weakness of these sedimentary units (e.g., Butler, 2004, Johnson et al., 2011). Mechanical data from Cambro-Ordovician powdered rocks, tested in rotary shear apparatus, examining frictional strength and stability of the gouges revealed that, unlike previously proposed, the rheological contrast caused by frictional weakness of the protoliths is not enough to explain the deformation localization observed in the field. Based on the results of our experiments, we posit that after an imposed episode of co-seismic slip, the metasomatized fine-grained clastic and carbonate- dominated lithologies exhibited a substantial shift from original frictional and stability behaviours that could plausibly explain the observed strain partitioning. During the propagation of an earthquake - widely reported to occur in compressional orogens, the frictional heat generated by slip at high velocities (>1 m/s) can induce mineralogical and physicochemical processes that lubricate faults (Di Toro et al., 2011, De Paola et al., 2015). Our work on the Cambro-Ordovician synthetic gouges suggest that further than lubricating faults during co- seismic slip, the occurrence of a seismic episode can trigger lasting changes in frictional strength and stability of fault gouges. These findings have interesting repercussions for earthquake propagation at shallower crustal depths and a fresh view of stratigraphical control in deformation localization within the rocks of Moine Thrust Zone foreland sequences.

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Present-day coexistence of different convergent boundaries along the Cyprus Arc

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Keywords: Eastern Mediterranean, Cyprus Arc, seismic reflection, convergent margins

Convergent margins are areas where two or more plates collide. Their tectonic characteristics may depend on the type of plate involved. For example, a convergent margin where an oceanic plate collides with a continental plate has different structures, both in terms of the geometry of the structures and their kinematics compared to a convergent margin involving two continental plates. In a general evolutionary scheme, a convergent margin may begin with intraoceanic subduction and end with a continent-continent collision that produces an orogen over geologic time. The most common approach to studying these systems is to analyze a fossil and exhumed convergent system, for example, by examining exposed rocks along an orogenic belt. However, the accuracy of paleogeographic reconstruction, which depends on sequential restoration of tectonic phases in these areas can be challenging, especially for ancient phases. One way to overcome this limitation is to select an area where different types of convergent margins are active today, i.e., an area where one can study convergent ocean-ocean, ocean-continent, and continent-continent margins. The Cyprus Arc system in the Eastern Mediterranean Basin is an example of the coexistence of different convergent margins. In this area, oceanic subduction to continent-continent collision is found from west to east, making it possible to study both the recent evolution of the area and to gain general insights to better understand the evolution of convergent margins. To this aim we used three regional seismic reflection profiles crossing the main structure of the area and, in particular, the convergent margins. Our data allow an accurate reconstruction of the evolution of these convergent margins from the Messinian to the Quaternary. They provide new insights into the geologic history of the area and a new example of how convergent margins develop when different plate types are involved.

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 temperature 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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Fast detection of complex deformation pattern associated to strong earthquakes from DInSAR measurements: the October 2016 central Italy case

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Keywords: Central Apennines, remote sensing, coseismic deformation, Monte Vettore Fault System

In the last three decades, remote sensing techniques, such as Differential Synthetic Aperture Radar Interferometry (DInSAR), Lidar differencing, optical imagery, and Global Positioning System (GPS) have been exploited for investigating, with high accuracy, ground displacement phenomena. Large seismic events (M_w > 5.5) can trigger deformations at the surface, such as ruptures related to the activation of main active faults and/or other deformations induced by seismic shaking (e.g., landslides, creeping, sinkhole).

In 2016–2017, a long earthquake sequence struck the Apennines in central Italy, producing impressive surface ruptures attributed to the 24 August Mw 6.0 and 30 October Mw 6.5 main-shocks. These ruptures were investigated and mapped by field geologists soon after the earthquakes.

We present detailed maps of the surface deformation pattern produced by the M. Vettore Fault System during the October 2016 earthquakes. The DInSAR analysis have been retrieved from ALOS-2 SAR data, via the Parallel Small BAseline Subsets (P-SBAS) algorithm. On these maps, we trace a set of cross-sections to analyse the coseismic vertical displacement, essential to identify both surface fault ruptures and off-fault deformations.

At a local scale, we identify a lower number of coseismic ruptures respect to the ones recognised in the field, but they are in very good agreement and even more laterally continuous. At a larger scale, we observe the M. Vettore Fault System hanging-wall being characterized by a long-wavelength upward-convex curvature, which is less evident towards the south and locally interrupted by a steep vertical gradient, testifying the occurrence of an antithetic NE-dipping fault.

A quantitative comparison of DInSAR- and field-derived vertical displacement reveals that our approach is particularly effective to constrain ruptures characterized by spatial vertical displacement up to 50 – 60 cm, which, in the field, show an unclear lateral continuity.

The rapid detection of deformation patterns from DInSAR technique can furnish important constraints on the activated fault segments, their spatial distribution and interaction soon after the seismic events. Thanks to the large availability of satellite SAR acquisitions, the proposed workflow can be potentially applied worldwide. It might be fundamental not only to support field geological mapping activities during an ongoing seismic crisis but also to provide a wider and faster picture of surface ruptures crucial for emergency management by civil protection in densely populated areas.

4D kinematics of extensional structures developed above discontinuous inclined ductile basal detachments: insights from analogue modelling

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Keywords: analogue models, evaporites, thin-skinned deformation, extension

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, most of these models did not consider variations in the lateral extent of evaporite layers, thus the influence of basal detachment extent, geometry, and discontinuities on four-dimensional fault growth and interaction is still not fully investigated.

The characteristics of rifted margins, such as width, length, presence of isolated structural lows due to active faults, may affect the salt deposition and distribution leading to a nonuniformly distributed salt layer within the same basin. In addition, the post-rift tectonics decoupled above salt layers is affected by, among others, direction geometry.

In this preliminary work, we focus on the role played by basal detachment lateral extent, geometry and discontinuities on the four-dimensional geometry and kinematics of normal fault systems, i.e., horsts and grabens, using three analogue models. Results of the models are used to analyse: i) timing and interaction of the structures; ii) cumulative displacement variation with extension (i.e., time); iii) interaction between basal detachment geometry and kinematics of developing faults.

The presented work uses results of three analogue models of thin-skinned extension prepared to simulate deformation of the brittle sedimentary cover above a ductile basal detachment (i.e., salt) in the brittle upper crust. Three different basal configurations have been modelled: i) a homogeneously distributed ductile detachment; ii) two sectors with a different distribution of the ductile detachment, separated by an abrupt, transversal boundary; iii) a laterally variable width of the ductile detachment, driven by an abrupt oblique boundary.

The amount of deformation along each fault, was calculated as the variation of the fault vertical displacement through time, by tracing both the fault hangingwall and footwall cut-offs on the model's surface DEMs, at every stage of deformation.

Results show how the geometry and kinematics of faults strongly depends on: i) the geometry of the ductile-brittle interface, ii) the spatial distribution of the basal detachment, and iii) the space allowing deformation to propagates.

Understanding the hidden tectono-metamorphic evolution of Precambrian rocks: integration of quantitative microstructural and microchemical analysis on the Boulder Creek batholith rocks (Front Range, Colorado, USA)

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Keywords: X-ray chemical maps, microtextural analysis, Precambrian geology, Boulder Creek batholith

In Precambrian rocks, the role of multistage deformation and/or subsequent orogenic events results in a superimposition of different fabrics and mineralogical associations that hinders the reconstruction of their tectono-metamorphic evolution. Although outcrop studies for the description of geometrical overprinting relationships are fundamental tools in structural geology, they need to be integrated with quantitative microstructural and chemical data to clearly understand these particularly old geological contexts (Zucali et al., 2021). The Boulder Creek batholith is a Paleoproterozoic intrusion made by two suites: (i) the Boulder Creek granodiorite (1714±5 Ma; Premo & Fanning, 2000) and (ii) the Twin Spruce Quartz Monzonite (ca. 1700 Ma). Its rocks have probably been originated from partial melting of the upper mantle and lower continental crust (Mahan et al., 2013). Quantitative parameters as grain size distribution and orientations, calculated for different mineralogical phases (i.e., micas, feldspars and quartz) could be combined with EMPA microchemical data (WDS/EDS X-ray elemental maps and WDS quantitative point analyses) to discriminate different generations of fabric elements and their related parageneses. This procedure has been applied on a biotite gneiss occurring in the Boulder Creek batholith, showing microstructures typical of partial melting, whose genesis and age are still debated. We applied the Min-GSD method (Mineral-Grain Size Distribution; Visalli et al., 2021) on high-resolution thin-sections optical scanning coupled with the Q-XRMA (Quantitative X-Ray Maps Analyzer; Ortolano et al., 2018) to respectively derive quantitative textural and compositional data for different tectono-metamorphic events. The above-described combination of data has also been used to calculate modal percentages for whole-rock composition and derive thermobarometric estimations from X-ray calibrated elemental maps, giving temperatures ranging between 600-660 °C and minimum pressures of about 5 kbar.

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Neotectonics in southern Sardinia: insights from the Cala Mosca site

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Keywords: Quaternary, luminescence dating, uplift, subsidence, horst and graben

Sardinia Island is located in the centre of the western Mediterranean area, and it has been considered tectonically stable since the Early Pleistocene. The marine sequence of Cala Mosca is considered one of the key paleo sea-level markers for the Marine Isotopic Stage (MIS) 5e highstand (116-126 ka), and it has been used as a proxy to calibrate the Mediterranean Pleistocene sea-level curve and to support the tectonic stability of the island. However, a chrono-stratigraphic review demonstrated that the marine sequence consists of two superimposed marine events divided by a composite unconformity surface. Performed luminescence dating related the two events to 137±7, 134±7 ka and 92±6 ka, respectively, and thus associated with highstands during the MIS5e and MIS5c substages.

The stratigraphic superimposition of these two highstands, both placed above present sea level (~+5 m), conflicts with the global accepted sea-level curve, according to which the mean position of MIS5e is placed above the present sea level (+5-9 m) whereas the MIS5c is worldwide accepted to be below (-22 m) the modern coastline.

Possible hypotheses to explain such a chrono-stratigraphic framework are: i) the MIS5c highstand is still not well constrained in amplitude and elevation compared with the present sea-level positions; ii) the Quaternary Relative Sea Level curve of the Mediterranean is characterized by unrecognized high-frequency sea oscillations; iii) regional and/or local tectonic activity affected the island during the late Pleistocene.

Assuming the first two hypotheses are questionless and focusing on the last one, we tentatively explain the stratigraphic setting of Cala Mosca in the context of the fault-bounded blocks asset of southern Sardinia. Two master faults bound a large-scale graben structured into two tectonic basins separated by a structural high where the Cala Mosca site is hosted. Note that low-magnitude earthquakes have been recorded along these faults and high-resolution GPS dataset point out to vertical movement of the blocks up to 1.5 mm/a. Also, geomorphic evidence of a generalized uplift, as inverted relief and deep river incision are widespread in the whole Sardinia block.

The absolute vertical movement of the Cala Mosca block will be positive or negative depending on the prevailing uplift or fault slip rates, respectively. After depositing the MIS5e deposits (+5/9 m), the Cala Mosca block have been displaced downward to approach the MIS5c highstand (-20 m), allowing the superimposition of the two marine events and the formation of a composite marine terrace; once formed, it have been uplifted toward the present position.

Although the kinematics and dynamics of this differential tectonics are far from being fully understood in this area, the proposed model may explain the controversial occurrence of composite marine terraces considering the worldwide accepted sea-level curve, leading to reconsidering the Sardinia tectonic stability paradigm.

The Ordovician Sardic and Sarrabese phases in the South European Variscan Belt: correlation between Sardinia, Eastern Pyrenees and Occitan Domain

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Keywords: Gondwana, angular unconformity, Ordovician volcanic arc, paleogeography, pre-Variscan geodynamics

Evidence of Ordovician tectonics is well preserved in the Variscan terrains now scattered in the circum-Mediterranean areas. It was in SW Sardinia (the External Zone of the Variscan basement) that was firstly detected the so-called Sardic Phase, a folding event that affected only the Cambrian-Lower Ordovician succession, and the related angular unconformity (Sardic unconformity). At a later time, a folding event (Sarrabese Phase) affecting a Cambrian-Lower Ordovician succession and an angular unconformity (Sarrabese unconformity) have been detected also in SE Sardinia, in the shallowest tectonic unit (Sarrabus Unit) of the Variscan Nappe Zone, and the Sardic and Sarrabese phases (and their unconformities) were considered the same event.

However, comparing the Cambro-Ordovician succession, the tectonic structures and the bio-stratigraphic data, relevant discrepancies arise between the External and Nappe Zone, suggesting that these domains did not share the same geodynamic setting and paleogeography in pre-Variscan times. Noteworthy are the different extent of the unconformity-related gaps (17 and 6 Ma in the External and Nappe zones, respectively), a lower Cambrian thick limestone formation outcropping only in the External Zone, and the occurrence only in the Nappe Zone of a subduction-related magmatic arc that seals the Sarrabese unconformity. Note that the activity of the volcanic arc in the Nappe Zone is contemporaneous to the continentalization and erosive processes in the External Zone. Furthermore, the Upper Ordovician succession in the External Zone defines a rift that evolve to a passive margin, whereas in the Nappe Zone the onset of a passive margin is marked by a nonconformity above the volcanic arc. This evidence supports the idea that the Sardinian block consisted of two distinct, not contiguous terranes before the Variscan Orogeny, entailing alternative correlations and an adjustment of the arrangement of the now scattered Variscan terranes.

The Eastern Pyrenees and Occitan domains show Ordovician features similar to that of Sardinia, and up to now, in several paleogeographic reconstructions, Sardinia, Pyrenees and Occitan domains have close positions. However, comparing the stratigraphic and tectonic features in view of the evidence exposed above for the Ordovician of Sardinia, we infer that also in the Paleozoic basement of the Pyrenees and Occitan domain two distinct pre-Variscan terrains can be recognized. This suggests a correlation either with the External or the Nappe Zone and an involvement in two different geodynamic settings, according to the Sardic or Sarrabese tectonic evolution styles.

To conclude, the data from the Ordovician of Sardinia could be an interpretation key for a more accurate reconstruction of the early Paleozoic paleogeography of Gondwana as well as the complex dynamics that led to the Variscan Orogeny.

Preserved lawsonite in the blueschist-facies ophiolitic bodies from the Albergian Unit (Ligurian-Piedmont zone, Western Alps)

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Keywords: lawsonite, thermodynamic modeling, tectono-metamorphic evolution, Liguria-Piemonte zone, Western Alps

Lawsonite-bearing metamorphic rocks, characteristics of HP facies conditions, are regarded as major markers of exhumed fossil subduction zones. Studies on these rocks and their tectono-metamorphic evolution give fundamental constraints to define tectonic processes driving subduction and exhumation of orogenic belt.

In the Western Alps, resulting from collision between European and Adriatic continental paleo-margins following the closure of their interposed Ligurian-Piedmont ocean by subduction, lawsonite-bearing rocks have been described both in oceanic- and continental-derived units.

Among the units belonging to the Ligurian-Piedmont zone, the here considered Albergian unit (AU hereafter) is extensively exposed in the Susa and Chisone valleys (Italian Cottian Alps) and comprises a thick sequence of calcschists with minor meta-ophiolitic bodies; occurrence of metastable lawsonite has been envisaged in the metasediments (Caron, 1977; Servizio Geologico d'Italia, 2020).

Considering the AU section exposed in the Monte Albergian – Gran Mioul area (Upper Chisone valley), the aim of this contribution is: (i) to document the occurrence of fresh lawsonite also in the meta-mafic rocks and, (ii) to constrain the tectono-metamorphic evolution of one of these meta-mafic bodies. In the considered area, the AU consists of a kilometric body of diabase meta-breccias (with minor meta-gabbros and meta-plagiogranite clasts and blocks), covered by discontinuous bodies of quarzitic meta-sandstones, black micaschists, and eventually a thick sequence of calcschists. Through detailed petrographic and minero-chemical studies of these lithologies, preserved magmatic textures have been recognized in the meta-mafic clasts, and the occurrence of metastable lawsonite, only partially replaced by retrograde mineral phases, has been investigated (Corno et al., 2022).

The isochemical phase diagrams approach (i.e. P-T pseudosections), applied on an Mg-Al meta-gabbro and a meta-breccia with plagiogranite clasts allowed to constrain the metamorphic peak in the lawsonite blueschist-facies, at about 18-21 kbar and 380-430 °C, followed by a partial re-equilibration in the epidote-stability field. The estimated peak P-T conditions and the preservation of abundant fresh lawsonite imply that the AU experienced a cold subduction followed by fast exhumation.

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Structural architecture and tectono-metamorphic evolution of the Briançonnais units in the Aiguilles de Chambeyron - Dents de Maniglia Massifs (France, Italy)

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Keywords: Geological mapping, Western Alps, Metamorphic wedge, Polyphase deformation, RSCM

The Western Alps transect of the Ubaye – Maira Valley studied in this contribution represents a unique geological section from the anchizone facies Helminthoid Flysch Units to the high pressure blueschist Schistes Lustrés Units (Michard et al., 2004). Between these Alpine Tethys-derived tectonic units, a stack of several Briançonnais-derived units is present. Each of this units have a different metasedimentary sequence from Carboniferous to Eocene, variably detached and deformed, and metamorphic grade, the latter ranging from sub-greenschist to blueschist facies (Gidon, 1958; Le Guernic, 1989; Gidon et al., 1994; Michard & Henry, 1988; Michard et al., 2004). The aim of the work was to reconstruct the architecture the Briançonnais units along this transect and to infer their tectono-metamorphic evolution. A particular aspect of this transect is represented by the post-metamorphic peak backfolding and backthrusting, here dominating the structural setting of the Briançonnais Units (Michard et al., 2004, Michard et al., in press). A geological- structural map of the area is presented at the scale 1: 15.000, highlighting the different units, their tectonic contact, metamorphic grade and stratigraphic sequence. Four deformation phases are identified in the study area: (1) a rarely preserved earlier phases D1 connected to the nappe stacking, (2) a successive phase which fold the previous surfaces, associated to a S2 foliation, well recognizable mainly in the hinge of F3 folds, (3) the main deformation phase, D3, connected to the NE backfolding (F3) and later backthrusting, (4) a later, shallower phase, forming minor upright kink-like folds with nearly E-W oriented axis, that we link to late strike-slip fault activity. During the field mapping numerous oriented samples have been collected for microtectonics and RSCM analysis (Beyssac et al., 2002; Lahfid et al., 2010). Microtectonics study allowed to make key-observations on the tectonic contacts kinematics, on the polyphase deformation and on the dynamic recrystallization regimes of main minerals. The metamorphic imprint, at a first glance in the field, appeared relatively weak with only few metamorphic minerals associated. Therefore, in samples with carbonaceous material, thermometer based on RSCM spectroscopy, was performed in order to estimate the Alpine metamorphic peak temperature in each unit. The estimated temperature ranges from 294 °C in the more external unit up to 345 °C of the innermost Acceglio s.l. units. Finally, critically linking observations made in the field and in laboratory and available literature, it was possible to reconstruct the structural architecture and tectono-metamorphic evolution of the studied transect, to suggest a paleogeographic restoration of the Briançonnais paleomargin and to do some considerations on the subduction/exhumation dynamics of the Briançonnais Units.

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Thermal ages on a subduction thrust, northern Hikurangi Margin, New Zealand

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Keywords: thermochronology, apatite, IODP, Expedition 375, Pāpaku fault

The Hikurangi Subduction Margin, a region that is known to host both shallow slow slip events (SSE's) 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 Holocene sediments (silt and clay), mud- and siltstones, and turbidites in the hanging wall, fault zone, and footwall, near the deformation front of the northern Hikurangi Subduction Margin. The top of active splay fault, 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 of thermal events in the region associated with the thrust fault, low temperature thermochronology (apatite fission-track – AFT, and U-Th/He – AHe) was applied in 10 samples of silt and siltstones from Site U1518. Samples near the Pāpaku fault zone display a large scatter of AFT and AHe single grain ages and the oldest ages. The outer zone of the hanging wall and footwall show less dispersion and relatively younger ages. The hanging wall AFT ages 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. The footwall AFT ages record the age of the Hikurangi Plateau (ca. 120 Ma). The younger central AFT (63.9 ± 8.9 Ma) and mean AHe (5.9 ± 0.2 Ma) ages of the hanging wall in relation to the footwall (AFT: 123.2 ± 38.9 Ma; AHe: 7.7 ± 0.7 Ma) show frontal tectonic erosion in this part of the subduction margin.

The latest reactivation of the San Carlos and the Liordes fault systems (Picos de Europa region, NW Spain)

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Keywords: fault reactivation, Alpine orogeny, clumped isotope geothermometry, San Carlos fault, Liordes fault

The Picos de Europa (PE) limestone massif is mainly constituted by Carboniferous units formed in the foreland of the Variscan orogen in NW Spain, recording deformation since the latest stages of the tectonic Variscan cycle. The area was 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 the Mesozoic, the area was affected by extensional deformation, with the development of the Basque-Cantabrian Basin 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 contraction in the Cenozoic overprinted earlier deformation in this region, giving rise to the Cantabrian Mountains.

The San Carlos and the Liordes fault systems (SCFS, LFS) are long-lived structures of kilometric scale traversing the southeastern sector of the PE, with NW-SE and WNW-ESE trends, respectively. The focus of this study is the reactivation history of the SCFS and the LFS, based on fieldwork and clumped isotope geothermometry applied to fault-related carbonate precipitates. For each fault activity period, syn-kinematic samples encompass slickenfibres on fault surfaces, fault-related veins and breccia cements, while post-kinematic specimens comprise calcite and dolomite veins.

In the SCFS, slickenfibres consistent with a dextral displacement show temperature values between (5-64) oC. In the LFS, slickenfibres recording dextral to oblique dextral reverse displacements present temperature values between (90-117) oC. Based on the temperature estimates and local cross-cutting relationships, these relatively-low-temperature (low-T) samples have been distinguished from a broad higher-temperature (high-T) set. The latter comprises older slickenfibres on normal faults, carbonate cement in sulphide-bearing breccias, and dolomite and calcite veins hosted along pre-existing structural discontinuities. The high-T slickenfibres register (207-240) oC and (199-253) oC temperature ranges in the SCFS and the LFS, respectively.

The clumped isotope signature is susceptible to resetting under certain circumstances. It is uncertain whether the high-T samples record real or apparent temperature, which depends on their age and the burial history. In contrast, the younger low-T samples show their original precipitation temperature, being here attributed to the Cenozoic Alpine contraction. Thus, a dextral to dextral-reverse displacement of the SCFS and the LFS is assigned to the Alpine orogeny. The temperature difference between the low-T samples in the LFS and the SCFS can be interpreted as the result of a deeper position of the LFS samples in the initial stages of the Cenozoic contractional deformation and different degrees of tectonic exhumation caused by displacement along the Alpine basal thrust of the Cantabrian Mountains.

3D virtual outcrops: a new way for data processing

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Keywords: Digital Outcrop Model, DEM, Photogrammetry, Sequence Stratigraphy, Geological Interpretation

In Geoscience, Digital Outcrop Models (DOMs) are by now an undoubtable advantage for educational, field-work and -trips, as well as research purposes. Moreover, in recent times, the global Covid-19 pandemic made field surveying very difficult, necessitating new investigation tools, such as photogrammetry. Although there are several different survey methods and software solutions for visualisation, there are still challenges in processing and displaying the large data volumes. In here, we show DOMs from Central Sicily from the Rocca di Cerere UNESCO Global Geopark. These were acquired from a DJI quadcopter drone (Unmanned Aircraft Vehicle – UAV), with and without Ground Control Points (GCPs) and Control Points (CPs) aid. The total areal coverage is around 7 km^2 with c. 480 meters of relief from which we have been able to create DOMs with an overall resolution of 4-5cm/pixel. Despite the large area, comparative tests with satellite images and regional DTMs show an overall good precision and accuracy of our outputs (DEMs and DOMs). Although for visualization and general purposes a high accuracy is not required, for stratigraphic and geological interpretations accuracy is pivotal. However, are virtual measurements as precise and accurate as they can be if manually acquired in the field? In here, we want to test the reliability of our virtual linear thickness measurements and geological/stratigraphic trends using both photogrammetric and interpretative software, respectively Agisoft PhotoScan and VOG-Lime. These preliminary analyses are essential to support any farther interpretation to establish detailed tilt histories and to provide a framework for correlating eustatic sea-level variations within the outcrop area.

How topography records the influence of inheritance on active rifting in the Shanxi Graben, North China

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Keywords: Rifting, Structural Inheritance, Geomorphology, North China, active tectonics

Many rifts are influenced by pre-existing structures and heterogeneities during their evolution, a process known as structural inheritance. During a rift's evolution, these heterogeneities may aid the nucleation of the rift, growth and segmentation of faults, aid linkage of various segments or even inhibit the formation of faults in various places. Structural inheritance is well explored in offshore rift settings due to the availability of high-quality 3D seismic, which enables good constraint on the structural evolution. However, the degree of structural inheritance in onshore active rifts is more difficult to constrain due to a lack of subsurface datasets. Yet, understanding how structural inheritance influences early rift evolution is vital to better understand seismic risk in areas of active rifting. The Shanxi Graben in the North of China is a densely populated active rift system that is believed to have formed along the trend of the Proterozoic Trans North China Orogen. However, the influence of these Proterozoic structures on the present-day rifting is poorly constrained. Here we show how the impact of structural inheritance on a young active rift may be investigated using tectonic geomorphological techniques - e.g., hypsometric integral, channel steepness (KsN), local relief and drainage network analysis. Using the geomorphic expression of active faults, we can quantify their geomorphic response and identify faults that show higher levels of activity. Our results show that large basin bounding faults broadly follow the trends of basement fabrics but show a lower geomorphic response, while smaller fault segments that link the main basins show higher levels of geomorphic response but often crosscut the basement fabrics. We interpret that those large faults formed first in regions with basement fabrics that were preferably orientated to the principal stress direction. Faults in the linkage zones between major basins likely formed later due to local perturbations of the stress field by the major rift faults. This means that there is no need for a changing stress field during the evolution of the Shanxi Graben, as previously proposed, but that the graben evolved under a relatively uniform stress field. Using geomorphic indices such as the hypsometric integral may also be applied to other areas with active rifts influenced by structural inheritance such as East Africa. Due to the lack of data in these regions, geomorphic analysis might prove useful in the study of the temporal evolution of structural inheritance in young active rifts.

C'-c method: a new refined kinematic vorticity gauge for mylonites combining shear bands and quartz Crystallographic Preferred Orientation

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Keywords: kinematic vorticity, shear zones, crystallographic preferred orientation, C' shear bands, Torngat Orogen, Scottish Highlands Scandian Belt

Many deformational processes in the crust include components of intense, localised strain accommodated by shear zones. As such, quantifying the deformation recorded in these structures is fundamental in understanding and reconstructing the tectonic evolution of Earth's lithosphere. The degree of non-coaxiality (expressed by the kinematic vorticity) is one of the most important deformation parameters of shear zones because it can be used to help understand the relative movement of the two blocks on the sides of the structure.This study proposes a new approach for quantification of the vorticity of kinematic flow in natural shear zones. 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 tilting 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 well match the vorticity numbers estimated with other approaches on the same structures obtaining a good match with the pre-existing datasets. In this study, we tested the C'-c method to the Abloviak Shear Zone (Torngat Orogen) and the Ben Hope Thrust (Caledonides of NW Scotland) obtaining the first vorticity data on these structures. Our data show that the C'-c method can increase the potential range of rocks in which it is possible to estimate kinematic vorticity. Our results also show that the C'-c method can be negatively affected by microscale kinematic flow partitioning, highlighting the importance of a detailed microstructure characterization of the studied rocks before any estimate of kinematic vorticity is attempted.

Using Sentinel–2 data for geomorphometric analysis of meandering rivers: Tectonic evaluation of Central Amazonia Region

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Keywords: river dynamics, sinuosity, neotectonics, tectonic geomorphology, Amazon basin

Freely-meandering rivers are sensitive indicators of neotectonic activity that is otherwise difficult to detect in low-relief areas. In this study sinuosity analysis has been carried out on 20 main rivers and tributaries of Central Amazonia Region as an aid for localization of river channel patterns influenced by on-going tectonic activity.

The main problem of such studies, however, the availability of accurate river channel data. For the Central Amazonia Region highly accurate dataset that has a good geographical coverage is hardly available. Consequently, the first objective of this project was to develop a data processing method of high-resolution satellite images which provides a quick and accurate way to digitize river sections of a large part of the intracratonic sedimentary basin. Furthermore, this work aims to detect channel sinuosity changes that could indicate recent vertical crustal movements. To achieve this, the water courses were automatically digitized using Sentinel–2 data and classic sinuosity values were calculated using several window sizes. The distribution of sinuosity variations was analysed by classification and various representations of the calculated values like mapping, cross plots and sinuosity-spectrum.

As the visualization methods complement each other the variations in sinuosity values can be highlighted and verified in several aspects. By the results compared to former neotectonic studies, some significant sinuosity changes can be correlated to known faults. The mentioned sinuosity variations coincide with the location of NW–SE normal and thrust faults active since Pleistocene times and NE– SW Miocene normal faults supporting the idea that these structures may have been reactivated.

In conclusion, multi-window sinuosity index calculation applied to satellite data based digitized water courses is a useful tool for recognizing recent tectonic activity in large low-relief areas, such as Central Amazonia.

Up close and personal with a subduction channel: Subduction, underplating, and return flow recorded in the Cycladic Blueschist Unit exposed on Syros Island (Cyclades, Greece)

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Keywords: subduction zones, Cyclades (Greece), tectono-metamorphic history, metamorphic rocks

Subduction zones are fundamental drivers of Plate Tectonics, localize strain at the lithosphere-scale over millions of years, and host deformation transients such as megathrust earthquakes and slow slip events. However, the geometry and internal structure of the deep interface (~30-70 km) is poorly resolved by remote sensing techniques like seismic tomography, which limits our understanding of deep subduction dynamics. I will synthesize structural, metamorphic, and geochronologic data from exhumed metamorphic rocks exposed on Syros Island (Cyclades, Greece) to reconstruct the tectono-metamorphic history during Eocene subduction and exhumation in the Aegean. I will argue that subduction of structurally distinct coherent units occurred contemporaneously with exhumation of previously accreted tectonic slices, in a subduction channel, or conveyor-belt fashion. Distributed, ductile return flow along the top of a refrigerating slab achieved ~80% of rock exhumation from peak depths of ~50-60 km to crustal depths of ~20 km. This work provides the spatial and temporal resolution of subduction tectono-metamorphism that is needed to quantify interface thermal structure, timescales of accretion, evolving interface strength, and exhumation rates.

The role of fault damage zones and lithology contrast on permeability variations: the Torralba Fault case study (northern Sardinia)

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Keywords: Fault damage zone, Fluid flow, Permeability, Deformation bands, Sardinia

Deformation within fault volumes can be accommodated by a variety of deformation structures and may introduce permeability-heterogeneity and anisotropy. This study aims to better understand the relationship between the deformation structures and the induced permeability variations in highly porous uncemented siliciclastic rocks and low porosity, carbonate cemented rocks to study their combined effect on fluid flow.
The Logudoro basin in northern Sardinia was considered as a test site. It is a Burdigalian half-graben that includes mainly subhorizontal continental to marine deposits such as conglomerates, sandstones, limestones, and mudstones. The study describes the outcropping N-S striking extensional Torralba-fault.

The fault damage zone and the outcropping deformation structures were mapped in detail. Intensity and interconnectivity of the fractures and deformation bands networks were analysed following a topological approach of node- and branch-counting (Sanderson and Nixon, 2015). In situ permeability measurements were performed by means of a portable air-permeametre (Tiny Perm 3) in both, the footwall (FW) and hanging-wall (HW), in the uncemented sands including deformation bands as well as in the overlying carbonate cemented sandstones.

The damage zone width is about 30 m in the HW and 15 m in the FW and maximum fault offset is 15 m. Deformation in the HW is accommodated by cataclastic deformation bands as single bands and clusters in the siliciclastic sands and by open karstified fractures with visible slip surfaces in the overlying carbonate cemented sandstones. Deformation bands and open fractures are connected i.e., they form continuous structures. The siliciclastic sands in the FW show no deformation bands and open fracturing in the carbonate cemented sandstones is less intense with no visible slip. Permeability in the siliciclastic sands is about 1-2 orders of magnitude lower than in the carbonate cemented sandstones. Deformation bands decrease the permeability in the siliciclastic sands of about one order of magnitude. Bulk permeability for both lithological units is about two orders of magnitude lower in the FW than in the HW.

Deformation bands decrease permeability of the host rock, whereas the upper laying karstified fractures represent an increase in permeability i.e., they form open channels to fluid flow. So, even having the opposite effect on permeability both deformation products will act in the same way to fluid flow, enhancing fault parallel flow and inhibiting cross to the fault flow. Deformation structures and permeability shows an asymmetric damage zone.

Sanderson, D.J. and Nixon, C.W. (2015) 'The use of topology in fracture network characterization', *Journal of Structural Geology*, 72, pp. 55–66. doi:10.1016/j.jsg.2015.01.005.

Development of low angle normal faults and rich in Boron hydrothermalism during the Early Permian in the central Southern Alps (N Italy)

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

During the Early Permian after the Variscan orogeny, the Alpine region was characterized by an extensional regime associated to crustal thinning and intense magmatic activity developed at different crustal levels. At that time, in the central Southern Alps (cSA), the opening of intracontinental fault-controlled extensional basins filled with volcanics and volcanoclastic sediments was controlled by a combination of Low- and High-Angle Normal Faults. The following Alpine shortening frequently reactivated and inverted the favourably oriented Permian normal faults, however some parts of these Early Permian Low-Angle Normal Faults (LANFs) exceptionally escaped the deformation, preserving their original features. These faults developed at the Variscan basement-sedimentary cover interface, and their fault core is characterized by cataclastic bands often sealed with cm to dm thick layers of dark cryptocrystalline to microcrystalline tourmalinites (Zanchetta et al., 2022). Tourmalinites are metasomatic rocks composed up to 70% in volume of tourmaline, produced by the circulation of Boron-rich fluids. In the cSA, they are recurrent in various sites along several kilometres (De Capitani et al., 1999), and are invariably located along Permian structures. Their age is indirectly constrained by their occurrence both along Early Permian faults (especially LANFs), and in Permian conglomerates, where they are included as clasts.

According to this evidence, tourmalinites are related to Permian tectonics, however their genesis has never been deeply investigated, even if they are likely linked to the Uranium mineralization of Novazza-Val Vedello district by several authors (e.g De Capitani et al., 1999). To further characterize and assess the source of the hydrothermal activity responsible for Boron-rich fluid circulation during the Early Permian intracontinental extension in the cSA, we studied several tourmalinite-bearing LANFs in different sites. We applied a multidisciplinary approach: field-based structural analyses are combined with mineral and whole-rock geochemistry, geochronology, microstructural studies and determination of Boron isotopic composition. Preliminary results demonstrate a temporal and geochemical relationship between tourmalinites and Early Permian magmatism, exalting the role played at regional scale by the extensional fault system as preferred pathway for circulation of fluids of magmatic origin at shallow crustal levels.

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The scale impact on fault and fracture processes: insights from new analogue modelling materials and outcrop-scale models

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Keywords: Analogue modelling, granular materials, dynamic scaling, fault damage zone

Fault and fractures represent the most common geological features and have a critical impact on the mechanical strength and fluid flow processes of rock volumes. They occur at all the observable scales, from the regional scale of fault systems to the micro scale of fracture sets and micro cracks.

Analogue modelling techniques play a primary role in the investigation of structural, kinematic and mechanical aspects of faults and fractures systems. In detail, dynamically scaled experiments allow the direct comparison between model and natural prototype. The geometrical scaling factor defines the model resolution (model/prototype length equivalence) and depends on the mechanical properties of prototype and model material. Therefore, the choice of the analogue material is critical for the definition of the model resolution.

Granular materials like quartz sands show a non-linear strain-dependent deformation behaviour similar to brittle rocks and are ideal for the simulation of upper crustal deformation processes (Panien et al., 2006). We developed a new Granular Rock-Analogue Material (GRAM) for the simulation of fault-fracture processes at the structural scale (Massaro et al., 2021). GRAM is an ultra-weak sand aggregate composed of silica sand, hemihydrate powder and water, capable to deform by tensile and shear failure under variable stress conditions. Mechanical tests showed that GRAM has a similar stress-strain curve as dry silica sand and a geometrical scaling factor $L^* = L_{model}/L_{nature} = 10^{-3}$ (1 cm in model = 10 m in nature).

We performed strike-slip experiments series at various scales, by applying different materials. Quartz sand models, with the resolution of the field scale (100 m to 1 km), were compared to the outcrop scale (1 m to 100 m) models obtained with GRAM.

The analyses of displacement and strain components at different stages of displacement enabled the comparison of the different structural styles characterising the models. The outcrop scale modelling enhances the investigation of the deformation processes occurring within the fault damage zone, which cannot be observed with a field scale resolution. Therefore, the combination of dynamically scaled models at different scales can ensure a better understanding of the geological process, encompassing structures and processes occurring at different scales. The application of the developed GRAM in scaled experiments can provide new insights to the multi-scale investigation of complex deformation processes with analogue modelling techniques.

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Climatic control on the location of magmatic arcs

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Keywords: volcanic arc, numerical modeling, climate, Southern Andes, deformation

Orogens and magmatic arcs at convergent plate margins are primary surface expressions of plate tectonics. Although it is established that climate affects the shape, size, and architecture of orogens via orographic erosion gradients, the upwelling of magmas and surface location of magmatic arcs have been considered insensitive to climate. The Southern Andes and the Cascade Range in the western convergent margin of South and North America, respectively, present a precipitation gradient due to high latitude westerly winds interacting with the topographic barrier. In these sectors, the orographic effect generates an increase in erosion rates on western slopes and an eastward migration of the topographic water divide. Geochronologic data reveal westward migration of late-Cenozoic magmatic activity and Quaternary volcanoes are systematically displaced towards the region of enhanced erosional unloading. This observation lacks a clear tectonic explanation. To adress the possible contribution of orographic erosion on the magma upwelling, we use a fully coupled geodynamic and landscape evolution numerical model and run two sets of numerical simulations. The first set of experiments compares magma upwelling paths when the initial topography is directly above, and shifted laterally, with respect to a pre-imposed mantle melting region. The second set of experiments accounts for asymmetric erosion of a topographic wedge initially centered with respect to the mantle melting region. Results show that the bulk strain and magma upwelling is symmetric when the topography is directly above the mantle melting region without imposed erosion. When the topography is initially lateral, or shifts laterally due to asymmetric erosion, the bulk strain and magma upwelling is asymmetric, feeding volcanism toward the region of enhanced erosion. We thus show that topographic changes due to orography can force a shift in the strain pattern that drive magma upwelling towards the region of topographic unloading. Considering the different structural settings between the Southern Andes and the Cascade Range, the orographic erosion gradient seems the most plausible shared causal mechanism behind the observed late-Cenozoic westward migration of regional magmatic activity.

Time-related changes in calcite intracrystalline deformation during a syn-collisional exhumation: an example from a low-angle normal fault in central Himalaya

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Keywords: marble, crystallographic preferred orientation, twinning, South Tibetan Detachment System, rheology

Crustal scale exhumations result in changes in mineral chemistry and deformation features of the involved rocks, including texture and crystallographic preferred orientation (CPO). Considering the different strain memories of minerals and microstructures, it is possible to reconstruct the deformation conditions in different times of the orogenetic history. Among the main rock-forming minerals, calcite can develop completely different microstructures for different deformation conditions. Nevertheless, because of its relative low strain memory, a careful approach is required to unambiguously use them to infer regional scale processes.

The Annapurna Detachment in central Himalaya (Kali Gandaki Valley, Western Nepal) is a prime example of Low-angle normal faults active in a collisional setting during the Oligo-Miocene. It is part of the South Tibetan Detachment System, a regional element characterized by an inhomogeneous architecture along the belt. The detachment system affected two main units, the amphibolite facies Greater Himalayan Sequence at the footwall and the greenschist facies Tethyan Himalayan Sequence at the hanging wall. Despite the detachment has been mostly studied in those regions where quartz-bearing rocks crop out, lithologies vary along strike. The Annapurna Detachment involved pure and impure marbles, now exposed within a 1-2 km thick mylonitic zone. Carbonate rocks are strongly deformed, showing a top-to-the-north sense of shear defined by asymmetric porphyroclasts and oblique foliations. Microstructures indicate that calcite accommodated ductile deformation mainly through grain boundary mobility and twinning. CPOs data highlight that both mechanisms were active during the detachment shearing. The combination of calcite grain size, twin density, oblique foliations orientations, CPOs asymmetries, and petrographic observations indicate that the two mechanisms dominated on each other at different deformation conditions. Deformation temperatures and strain rates decreased from the deformation stage dominated by grain boundary mobility to the late deformation stage dominated by twinning, while differential stress increased. Both deformation events occurred under almost constant general shear conditions, unlike what has recently been observed in the nearby Lower Dolpo region in Western Nepal (Nania et al., 2022). These results indicate that marbles experienced different deformation paths along strike, highlighting the influence of rheology and long lasting deformation for low-angle normal faults, and contributing to the regional knowledges on the tectonic evolution of the South Tibetan Detachment System in Himalaya.

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Investigating the variability in Quaternary mud deposition based on seismic surveys offshore Balatonboglár, Lake Balaton

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Keywords: sedimentation, stratigraphy, seismics, Lake Balaton, sequences

In order to study the evolution and sedimentation of Lake Balaton, there have been geophysical surveys since 1981. Based on these surveys, we can investigate the Late Pleistocene – Holocene sediments of Lake Balaton in ultrahigh resolution, decimetre scales. Offshore borehole data shows that the formation of the lake was about 17000 – 15000 years BP and the lower part of lake sediments consists of siliciclastic sequence while the upper part is calcareous mud. In the late glacial - Holocene period the course of the sedimentation varied with climate and related lake level changes. These changes had effects on sedimentation and resulted in variation in sedimentation rates both in time and space. The most important events in the lake's history can be seen in offshore seismic records. These events appear as pronounced reflections and changes in seismic facies. By interpreting the seismic profiles, we can find these events and can use them to describe the sedimentary processes.

In my work I have investigated lake sediments in an area of 2.5 km x 10 km near Balatonboglár. Based on offshore seismic surveys, I did the stratigraphic subdivision of the mud and an extensive seismic mapping using 57 ultrahigh resolution profiles. Subdivision has been done using sequence stratigraphic approach by identifying the most significant reflections and high order lacustrine sedimentary cycles. Thickness mapping of the derived sedimentary units showed that the course of sedimentation was different in different parts of the area. Based on my thickness maps I have got to the following main conclusions: (i) The Quaternary strata can be subdivided into 10 smaller units. (ii) In each units the sediment thickness is about few to several 10 centimetres and (iii) the rate of deposition varies spatially with differences over 30-40 centimetres. (iv) Comparing consecutive units, temporal changes can be also mapped and confirmed. (v) These characteristics are even true for the youngest lacustrine sequences.

All of this information provides important details on the sedimentation history of Lake Balaton and can be considered as a base of a new 4D depositional model of the area.

The Baunei area: a key sector to decipher the upper structural level deformation related to nappe-stacking during the Variscan orogeny

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

The concept of "structural level" is based on the change of the deformation style (or regime) with temperature and pressure variations (Fossen, 2016). Going deeper in the crust, deformation becomes more intense and ductile shear zones and ductile deformation drive the structural architecture. In collisional settings, the hinterland-foreland transition zone consists of a thick sequence of metasediments that underwent nappe-stacking deformation, pervasive shearing and folding, and low-grade metamorphism. This sector is characterized by km-scale ductile shear zones linked to thrust-sense shearing, which lead to the formation of thrust sheets or tectonic nappes. Although most of the deformation has been concentrated within the shear zones, non-coaxial deformation in upper structural levels could be accomodated by superposed generations of folds and cleavages. We performed a Raman Spectroscopy on Carbonaceous Material (RSCM; Beyssac et al., 2002) coverage of the Internal Nappe Zone (Carosi & Pertusati, 1990) of the Sardinian Variscan belt (Carmignani et al., 1994). This massive study has been fundamental to point out thermal anomalies linked to specific geological problems. In the Baunei area, an isolated eastward fragment belonging to the Internal Nappe Zone, we highlighted the presence of lower temperatures with respect to the other sectors of the Internal Nappe to the west. Detailed meso- and microstructural analysis highlights a polyphase evolution that resulted in a complex superposition of multiple foliations and folds. In particular, we recognized: (i) the original bedding (S_0); (ii) an early phase generally associated to a primary cleavage (D_1), (iii) two folding events with a top-to-the S-SW vergence (D_2a and D_2b) and (iv) upright refolding (D_3) with later brittle deformation. The lack of mylonites and the deformation characterized by folds with a SW vergence in agreement with the sense of shear along the basal tectonic contact (e.g., the Barbagia Thrust; Montomoli et al., 2018), coupled with lower RSCM temperatures, allow to recognize the structurally upper position of this sector within the nappe pile.

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Investigating co-seismic reactions in fault cores

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Keywords: Fluid-rock reactions, earthquake geochemistry

New materials are produced co-seismically in principal slip zone (PSZ) fault gouge, which effects fault strength, rupture style and propagation of future events. This work investigates these coseismic reactions over a range of mineralogy and seismic conditions to address the following questions: In what manner do newly formed materials affect fault strength? How do coseismic fluid-rock interactions aid fault sealing? Can we use stable isotopes as new tools to record mechanically driven processes? Coseismic reaction products can be identified and analysed by undertaking experiments where synthetic fault gouge of initially simple mineralogical composition in contact with hydrothermal fluid is exposed to seismic conditions using mechanical shearing apparatus. By incrementally increasing complexity of synthetic fault gouge mineralogy, it is possible to identify reactions that lead to documented products in natural gouge. The Alpine Fault, New Zealand, is an active plate boundary and ideal natural study site for investigating a wide range of tectonic processes. It will be used as a comparative source for natural samples. Fully characterising (mineralogically, chemically, and isotopically) these gouges and fluids, pre and post mechanical shear, is the first step in developing new methodologies that utilise geochemical and isotopic tools to build a mechanistic and quantified understanding of the processes governing earthquake slip and fault strength evolution. This work paves the way for exploring isotopic tracers of mechanical deformation more broadly in Earth Sciences, widely applicable to rock mechanics, structural geology, tectonics, and economic geology.

Investigating the impact of diverse methodologies for interpreting faults in the subsurface

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Keywords: fault interpretation uncertainty, fault interpretation methodologies, fault geometry

The ability to map faults is a fundamental requirement of almost all interpretations of subsurface geological structure, as imaged in 3D seismic volumes. However, few published studies provide detailed descriptions of the workflows behind such interpretations. These omissions inhibit assessment of risks of interpretational failures and uncertainties – essential for many aspects of applied geoscience (e.g. assessment of seismic hazard, future integrity of geostorage sites). Those interpretation methodologies that are documented routinely under sample (e.g. using spaced "in-lines") and smoothing – simplifications that can bias understanding of fault geometries. Here we examine the sensitivity of output fault geometries derived from a variety of interpretation workflows applied to a 3D seismic volume. The purpose of this work is to find out the influence of strategies during the interpretation of geological structures using high-resolution seismic data to improve accuracy, and uncertainty assessment in resulting structural models.

Using a high-resolution regional 3D seismic data-set, we applied a variety of different workflows. There are two distinct components to producing images of faulting patterns and the derivation of statistics of these populations – mapping and smoothing. Mapping was performed using vertical profiles and contrasted with fault-mapping in serial time-slices. Some of our mapping workflows used conventional under-sampling, others worked at full resolution. Faults were drawn using poly-lines and points, joined by line segments ("fault sticks"). Following this initial mapping, we were able to analyse each fault output and compare them. To these outputs, we applied different fault surface construction methods - which in turn are sensitive to the smoothing level of the method applied. Two strategies were employed, one using all elements of the initial fault mapping (poly-line traces and pick-points), the other only use (pseudo) tip points. We examine a single fault comparing the two obtained surfaces with its interpreted elements (points and lines).

Our results show that different workflows, both in mapping and in smoothing, generate distinctly different interpretations of fault geometry that in turn yield distinct statistics. Not only should interpretations of seismic volumes be accompanied by careful descriptions of the workflows behind them, multiple workflows should be used at least to initiate appreciation of the uncertainties in these interpretations.

How do geologists interpret faults?

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Keywords: fault interpretation uncertainty, fault interpretation methodologies.

The ability to map faults is a fundamental requirement of almost all interpretations of the subsurface geological structure, as imaged in 3D seismic volumes. Fault interpretation methodologies vary greatly depending on data quality and the interpreter's knowledge, experience, visuospatial reasoning skills and preconceptions. In this context, how do fault outputs differ applying different methods? This poster aims to run a little experiment and open the discussion about the impact of fault interpretation workflows. For further investigations, assistants are going to be asked to interpret twice a seismic section with different vertical exaggerations. We intend to enrich the understanding of the influence of strategies on the interpretation of faults using high-resolution seismic data and help correct bias to improve accuracy in resulting structural models.

The Jurassic rift-related fault system and its re-activation history (central Southern Alps, N Italy): clues from structural analysis and paleo-fluid characterization

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Keywords: Tectonic evolution, microstructural analyses, veins, Orobic Alps

The central-southern part of the Orobic Alps (Seriana Valley, Bergamo) is characterized by a complex polyphasic evolution (Zanchetta et al., 2015). On the right hydrographical side of the Seriana Valley, it is possible to observe tectonic structures, mainly developed in the brittle regime, such as thrusts, normal and strike-slip faults. Zanchi et al. (1990) identified at least three different deformative events thanks to structural analyses and cross-cutting relationships with magmatic bodies; the earliest phase is characterized by a N-S oriented normal faults system which is several kilometers long. These structures border a graben that formed between the Early Jurassic and 40 Ma (U-Pb on zircon; D'Adda et al., 2011). After the emplacement of E-W andesitic dykes, the normal faults were re-activated as sinistral or dextral strike-slip faults during the N-S oriented Alpine compression, that caused southward translation of the Dolomia Principale dominated thrust sheet, probably during the late Cenozoic (Zanchi et al., 1990).

The complex evolution of this area has only been hypothesized until now. Therefore, additional analyses are needed in order to better understand the complexity of the Alpine deformation in the central Southern Alps.

This work focuses on the area around the locality of Amora (Selvino, Bergamo), since here the main tectonic features are well exposed with clear cross-cutting relationships. First, structural analyses have been performed to reconstruct the geometrical features of the observed thrusts, normal and strike-slip faults, joints and veins; at least three tectonic phases have been identified, as described by Zanchi et al. (1990). Then, the focus was put on the early E-W oriented extensional phase, which formed the N-S oriented graben. These structures are of particular interest since their time of formation is not yet well constrained and since they played a key role during the Alpine compression. To investigate the possible syn-sedimentary activity of these normal faults and to constrain their probable Early Jurassic origin, mass-transport deposits (MTDs) clearly exposed in the hanging wall whitin the Moltrasio Limestone, have been studied in detail to reconstruct the direction of transport and the paleoslope orientation.

Microstructural analyses are in course on calcite veins sampled from the Norian to the Lower Jurassic successions exposed in the study area. These veins formed together with the main tectonic features, as suggested by the structural analysis. The aim of this work is to reconstruct their paleotemperature (with fluid inclusion and clumped isotopes analyses) and the time of their formation (with U-Pb geochronology), in order to constrain the main tectonic phases of activity and therefore, the evolution of the area.

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The Ferriere-Mollières Shear Zone (Argentera Massif, Western Alps): an example of a regional-scale strain softening 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. The shear zone is characterized by an increasing deformation gradient toward the center: the external part of the FMSZ is made of high-grade protomylonites while, moving toward the center, medium-grade mylonites and subsequently lower-grade ultramylonites occur.

The FMSZ evolved under decreasing temperature conditions, this confirmed by syn-tectonic minerals and by temperature values obtained with the opening angle thermometer of quartz c-axis applied on sheared rocks in different position within the shear zone (Simonetti et al., 2018, 2021). The study of kinematics of the flow, revealed that the deformation regime progressively changes along the deformation gradient from a pure shear-dominated transpression to a simple shear dominated transpression. 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. 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. 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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Thrust Fault Linkage through Rheological Multilayers

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Keywords: Thrust faults, multilayers, rheology, deformation

According to conventional textbook models of their formation, thrusts form from a base detachment and then quickly propagate upwards through a multilayer, branching off old faults at depth with a fault-bend fold forming in the hanging wall (Dahlstrom, 1969, Elliott & Johnson 1980). This "footwall collapse" model commonly fails to match up to actual field geological structures. In the alternative, stiff layer thrusting model, the thrust originates and localises in mechanically competent beams as ramps and the thrust tip propagates both up and down eventually to create a linked fault system (Eisenstadt and De Paor, 1987). This model has had few tests at outcrop level, so development of a singular model which can be applied across thrust systems is necessary. A first test has been applied to the duplex outcrop of Old Red Sandstones and mudstones at St Brides Haven on the west coast of Pembrokeshire in SW Wales, UK.

At Sassoscritto on the Calafuria coast just south of Livorno, W Italy the well-exposed strata provide ideal test multilayers as there is an abrupt rheological change between thickly bedded competent sandstone beds and the alternating siltstone-fine sandstone, thin-bedded turbidite facies. A detailed structural investigation using field and photogrammetric mapping has been applied to the low cliffs to investigate the evolution of the fault system. This is a little-studied outcrop 10m high and 100m wide which exposes a thrusted multilayer cut by steep over-printing normal faults. A complex duplex structure is confined within the largest thin-bedded package and characteristic bed parallel thrusts faults have developed in this unit either side of competent sandstone beams without any upwards propagation. There is strong evidence of stratigraphic controls on both thrust and normal fault growth and deformation, which are linked to variations in rheology and the location of existing structures.

The purpose of this work is to contribute further data to the composition of a new model for thrust formation from varying outcrop templates to enrich styles of deforming multilayers and mitigate bias resulting from overuse of the standard model of thrust formation, as abrupt changes in rheology are highly likely in most geological multilayers.

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Ramps first: Thrust localisation in a single competent layer

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Keywords: Thrust faults, multilayers, rheology, deformation

Interpreting fault systems and understanding fault geometry is highly uncertain and a major risk when developing resources in the subsurface, especially in fold thrust belts where seismic imaging is poor. Making more realistic models for fault geometry and localisation behaviours in multilayers is essential for reducing risk in subsurface engineering, such as geological disposal of radioactive waste. Researchers rely on conventional textbook models of thrust formation which are based on theory, but is the range of models enough?

As changes in rheology are likely in most multilayers standard models of thrust formation are often not appropriate. The purpose of this work is to test models of thrust formation with actual outcrop structures, to achieve a comprehensive understanding of the variation in localisation behaviour of thrusts, mitigating bias resulting from overuse of the standard models. In a "foot-wall collapse" model thrusts form on a base detachment and then quickly propagate upwards through a multilayer, branching off old faults at depth with a fault-bend fold forming in the hanging wall (Dahlstrom, 1969). This model commonly fails to match up to actual field geological structures. In a "stiff layer thrusting" model, the thrust originates and localises in mechanically competent beams as ramps and the thrust tip propagates both up and down slowly to create a linked fault system (Eisenstadt and De Paor, 1987). This model has had few tests at outcrop level, so development of a singular model which can be applied across thrust systems is necessary.

In the UK, thrust structures in the Old Red Sandstone are ideal test multilayers as they contain faulted competent sandstone beds encased in cleaved mudrocks. Field and photogrammetric mapping has been applied to the St Brides Haven outcrop on the west coast of Pembrokeshire in SW Wales, a little studied outcrop 10m high which exposes an open fold pair typical of Variscan thrust deformation (Hancock, 1982). The low cliff allows for detailed mapping of a complex imbricated Old Red sandstone-mudstone multilayer. The outcrop has an abrupt rheological change where faults are confined close to a single competent sandstone beam which varies in thickness up to 1m thick, with characteristic fault spacing along the beams and a developed cleavage in the mudrocks above and below the beams. There is strong evidence of sedimentological controls on thrust fault growth and deformation, which are linked to variations in rheology and cross bedding features. Mapping reveals that the cleavage trajectories in the mudstones vary into the beam and are then offset by the faults, indicating an irregular distribution in shear strain.

The polyphase Miocene extensional formation of the Hungarian and Slovakian part of the Danube Basin

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Keywords: Danube Basin, extension, Miocene, seismic interpretation

The Danube Basin is one of the largest sub-basins of the Pannonian Basin, forming a transitional zone of the Eastern Alps and the Western Carpathians, distributes between Slovakia, Hungary, and Austria. During the Miocene, the lithosphere of the Pannonian Basin underwent extensive rifting, which led to the formation of the Danube Basin. Several studies have been carried out about the opening of the Neogene grabens in the Hungarian and the Slovakian parts of the basin, but no uniform interpretation covering the entire Danube Basin has been made. It remained an open question whether, as in the case of the Miocene sub-basins of the Great Hungarian Plain (Balázs et al., 2016) and the SW Pannonian Basin (Fodor et al., 2021), a trend of spatial shift of basin opening and a temporal change on faulting can be observed in the Danube Basin region.

In this research, we were looking for the answer to the relationship between the major Miocene grabens in the study area and the order of the opening of these structures. The seismic interpretation of the Danube Basin using more than 150 seismic sections and data from approximately 300 wells has been performed. Based on the tectonic systems tracts (defined by Prosser, 1993) the delineation of the rift climax in the individual troughs has been carried out, which, when compared with the age of the sediments filling the troughs, can be used to estimate the time of the opening of the grabens.

With the outcome of this research, the troughs from both the Hungarian and the Slovakian parts could be examined together. From the results, it can be stated that in the case of the grabens of the Danube Basin, a pronounced west to east temporal trend, as in the sub-basins of the Great Hungarian Plain (Balázs et al., 2016) cannot be seen. Correlation of undeformed and deformed stratigraphic horizons between the sub-basins suggests that the grabens of the basin periphery opened earlier than the depressions in the central part of the basin; a conclusion similar to the work of Šujan et al. (2021) for the Slovakian part. So a temporal and spatial migration of the extension from the basin margin toward the basin center can be observed.

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Discontinuities network of the southern sector of Mont Chaberton (Western Alps)

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Keywords: Mechanical discontinuities, fracture network, Mont Chaberton, NW Italian Alps

Understating geometric relationships between mechanical discontinuities (e.g. bedding, foliations, and fractures) of rock mass is paramount in geosciences, providing fundamental data for geo-engineering and practical application.

Our research group is studying different geological contexts to characterize the network of mechanical discontinuities from outcrop investigations and compare it with main geoengineering parameters and derived rock-mass classification.

We report first results obtained in the southern sector of the Mont Chaberton (Claviere area, Italian Western Alps), where spatial arrangement and interaction between mechanical discontinuities have been investigated across a major fault zone. The area is characterized by tectonic juxtaposition of continental (Chaberton-Grand Hoche unit -CHB- of the pre-Piemonte zone) and oceanic units (Chenaillet -CHE- and Lago Nero -LN- of the Piemonte-Liguria zone) (Servizio Geologico D'Italia, 2020). The CHB unit consists of a thick succession of Triassic dolomitic marble, overlaid by Lower-Middle Jurassic calcschist with phyllite and levels of metabreccias of dolostone and basement rocks. The LN unit consists of serpetinite and meta-basalt wrapped by meta-ophicalcites, overlain by radiolarian meta-chert (Upper Jurassic), marble, and by a succession of prevailing calcschist with levels of marble and black metapelite (Cretaceous). The CHE, unaffected by Alpine metamorphism, consists of pillow lavas overlying gabbroic rocks and serpentinized mantle. The considered high-angle fault zone (NE-SW trending) separates a northern sector (with LN overlaid by CHB), from a southern sector (with LN under the CHE).

Discontinuities were sampled along several transects across the fault zone, using traditional linear scanline and circular-window methods (Wu & Pollard, 1995; Mauldon et al., 2001). Based on the observed displacement direction of the fracture planes, we distinguished joints (generally opening mode), shear fractures (faults), and veins. The spatial arrangement of the sampled discontinuities allows defining the discontinuity network based on type, orientation, and relationships between discontinuity planes. The network has been described in terms of topological relationships reflecting connection and distribution of discontinuities in the rock mass.

This study shows a variation of the topological indexes moving from the fault core towards the damage zone. Due to the importance of structural setting of rock mass in geoengineering applications, we tested possible correlations between parameters derived from a traditional geomechanical approach and the topological indexes.

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Interacting extensional systems of the Northern Peloponnese, Greece: Transition from syn-orogenic extension to Corinth rifting

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

In the northern Peloponnese, metamorphic windows (domes) recording Miocene syn-orogenic to back-arc extension of the Southern Hellenides on low angle detachments, lie directly south of the younger Pliocene-Pleistocene Corinth rift and interact with its southern margin fault system. Metamorphic windows contain high-pressure units of retrograde greenschist to blueschist quartzite-phyllite. HP units were emplaced during the Miocene syn-orogenic exhumation within the subduction channel on the footwall of the Cretan detachment. In this work, the interaction between the emplacement of high-pressure units within the middle-upper crust and the 3D extensional continental unroofing of the orogenic belt is documented at an unprecedented resolution. New structural and micro-structural data collected on the metamorphic domes document the ductile to brittle evolution of the Cretan detachment with mostly top to the ENE or NE shear bands overprinting the regional metamorphic foliation. Surrounding the metamorphic domes, the pre-rift Hellenides nappe stack was stretched by about 15-25 km by low angle extensional faults that root into the Cretan detachment that forms the main decoupling level in this area. These low-angle extensional faults contribute to the exhumation of the Quartzite-Phyllite metamorphic nappe. The low-angle extensional faults have both top to the NE or SW kinematic in the Central Peloponnese and top to the N kinematic in northern Peloponnese at the north-western termination of the metamorphic windows, immediately south of Corinth rift southern margin. Corinth rift E-W trending fault network is superimposed to these extensional inherited pre-rift structures. In addition, new field data in the northern Peloponnese indicate that continental sedimentation controlled by these low angle normal faults underlies in apparent continuity the Corinth syn-rift succession, which is itself controlled by later high angle rift faults. We integrate in a regional structural model the transition from the Miocene pre-rift syn to late orogenic Peloponnese extensional tectonic regime to early-stage Corinth rifting recorded in newly mapped depocenters located in the south-eastern Corinth basin between Stymfalia and Nemea.