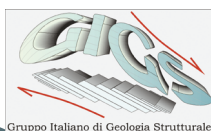


San Giovanni Valdarno (AR - Italy)  
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# ABSTRACT BOOK

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## **Tectono-sedimentary evolution of the Northern Apennines between Curone and Staffora Valleys (NW Italy): new constraints from geological mapping and chaotic rock units differentiation**

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**Keywords:** Northern Apennines, External Ligurian Units, tectono-stratigraphic evolution, olistostromes, broken-formations.

The Northern Apennines represent the remnants of a complex tectonic evolution occurred between European plate and Adria microplate from Late Cretaceous subduction to Cenozoic continental collision, and subsequent intra-continental deformation.

In the sector between Curone and Staffora Valleys, in the northwestern part of Northern Apennines, this multistage tectono-stratigraphic evolution is recorded by a complex structural setting characterized by the tectonic superposition between the External Ligurian Units (i.e. the ophiolitic-bearing chaotic complex of the Gropallo Unit and the non-ophiolitic Cassio Unit), the Middle Eocene - Miocene wedge-top basin Epiligurian Units succession, and the Late Messinian - Pliocene Po Plain succession. Our new geological map at the 1:20,000 scale (Barbero et al., 2017), based on (i) the crosscutting relationships between main faults and local to regional stratigraphic unconformities and (ii) the differentiation among different types of chaotic rock units (olistostrome and broken-formations), allow us to describe six main tectonic stages occurred from Late Cretaceous to Early Pliocene:

- Late Cretaceous-Early Eocene stage: the internal chaotic block-in-matrix fabric of the Late Cretaceous ophiolite-bearing Pietra Parcella Complex and of the “Basal Complexes” of the Cassio Unit (i.e., Argille Varicolori and Scabiazza Sandstones) document mass-transport and tectonic processes, respectively, occurred in the frontal part of the Ligurian wedge during subduction stage;
- Middle Eocene (Lutetian-Bartonian) stage: the widespread occurrence of Baiso argillaceous breccias, corresponding to a middle Eocene olistostrome, suggests a new gravitational instability period triggered by the tectonic uplift of the Cassio Unit;
- Late Priabonian-Rupelian stage: the deposition of the Ranzano Formation (late Priabonian - Rupelian) is controlled by the syn-tectonic activity of NE- and N-striking faults;
- Chattian-Early Miocene stage: the emplacement of olistostromes of the Val Tiepido - Canossa argillaceous breccias within the Antognola Formation depositional setting, is controlled by ENE-striking left-lateral strike-slip faulting, in turn sealed by Contignaco Formation (Late Aquitanian - Burdigalian).
- Late Serravallian-Tortonian stage: the unconformable deposition of the late Messinian Cassano Spinola Conglomerates onto the Argille Varicolori suggests a new tectonic pulse as documented by the occurrence of ENE-striking thrusts;
- Late Messinian - Early Pliocene stage: tectonic deformation triggered the gravity-driven emplacement of the Late Messinian Valle Versa Chaotic Complex and the reactivation of NW-striking faults.

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Barbero E., Festa A., Fioraso G. & Catanzariti R., (2017) - Geology of the Curone and Staffora Valleys (NW Italy): field constraints for the Late Cretaceous - Pliocene tectono-stratigraphic evolution of Northern Apennines. *Journal of Maps*, 13:2, 879-891

## **Preliminary petrological and stratigraphic data on the Band-e-Zeyarat ophiolite (Makran accretionary wedge, SE Iran)**

Barbero, E.<sup>1</sup>, Saccani, E.<sup>1</sup>, Pandolfi, L.<sup>2</sup>, Marroni, M.<sup>2</sup>, Delavari, M.<sup>3</sup>, Dolati, A.<sup>3</sup> & Catanzariti, R.<sup>4</sup>

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*Keywords:* ophiolite, Band-e-Zeyarat, Makran, Iran.

The North Makran is the innermost structural domain of the Makran Accretionary Prism (SE Iran). It consists of an imbricated stack of south-verging tectonic units and chaotic complexes, which are (from north to south): 1) the northern ophiolites (e.g. Band-e-Zeyarat ophiolite); 2) the Bajgan and Durkan Complexes that are described as continental-derived metamorphic complexes; 3) the Coloured Mélange. The northern ophiolites are generally considered as generated in a back-arc basin developed since Early Cretaceous between the Bajgan-Durkan microcontinents and the Lut Block (McCall & Kidd., 1982; Hunziker et al., 2015).

We present here preliminary petrological and stratigraphic data of the Band-e-Zeyarat ophiolites. This unit consists of an incomplete ophiolite sequence characterized by an intrusive complex (cumulate gabbros and dunite, isotropic gabbros, and minor diorites and plagiogranites) followed upward by a sheeted dike complex, which is capped by a volcano-sedimentary succession. This succession is characterized by pillow lavas passing upward to pillow breccias with decimetric slices of carbonatic sedimentary rocks, which gradually increase in abundance toward the top of the succession represented, in turn, by Barremian calcareous pelagic marls and limestones. Locally, the volcano-sedimentary succession is cut by dikes that feed some sills also intruded in the calcareous sedimentary rocks. New geochemical data on the volcanic and intrusive rocks indicate the occurrence of three distinct geochemical varieties: 1) rocks characterized by LREE depletion showing normal N-MORB affinity; 2) rocks showing slight enrichment in LREE and LILE, which are transitional between N-MORB and E-MORB; 3) rocks characterized by marked enrichment in LILE and LREE showing a clear E-MORB affinity. In contrast to most backarc basin magmatic rocks, the studied rocks show no subduction-derived chemical components. Rather, similar to rocks from many Iranian ophiolites, their enriched geochemistry suggests a formation from an enriched mantle source in subduction-unrelated oceanic basins or continental rift settings. Further geochemical, structural, and stratigraphic studies are necessary for providing robust constraints for the interpretation of the tectonic setting of formation of the Band-e-Zeyarat ophiolite.

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## **Geological mapping in the Victoria Land, Antarctica: filling the gap between the GIGAMAP and the GNS maps**

Capponi, G.<sup>1</sup>, Casale, S.<sup>2</sup>, Montomoli, C.<sup>2</sup>, Carosi, R.<sup>3</sup>, Cox, S.<sup>4</sup>, Crispini, L.<sup>1</sup>, Federico, L.<sup>1</sup>, Iaccarino, S.<sup>2</sup>,  
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*Keywords:* geological mapping, Convoy Range, Victoria Land, Antarctica.

In the austral summer 2017/18, in the framework of the 33rd ItaliAntarctide Expedition, a three person team performed geological and geological-glacial field mapping in the Convoy Range (Victoria Land, Antarctica), at the scale 1/250'000. Activity was heli-supported, starting from the Italian Mario Zucchelli Station, and interested two 1/250'000 quadrangles of the USGS Reconnaissance Series: the Convoy Range and the Franklin Island quads. The activity had two principal targets:

- to complete geological mapping for the area between 76° and 76°30' S, filling the gap existing between the area covered by the GIGAMAP programme (Pertusati et al., 2016) to the north and the geological maps by GNS Science (New Zealand) to the south (Gunn & Warren, 1962; Pocknall et al., 1994; Cox et al., 2012);
- to collect new data (stratigraphic, structural, sedimentological and petrographic data) to better characterize the lithotectonic units cropping out in the investigated area.

In Antarctica the activity included geological and geological-glacial field mapping, structural observations and rock sampling. In this area, the rocks of the Gondwanian sequence, i.e. the Ferrar Group and the Beacon Supergroup, are prevalent. The crystalline basement underlying the Gondwanian sequence occurs only in the sector that is close to the Ross Sea coast, where it is constituted by granites and granodiorites of the Granite Harbour Igneous Complex, with minor enclaves of Wilson Terrane gneiss.

During this activity, we collected rock samples (more than 120) for subsequent laboratory analyses to be done in Italy and also gathered attitude measurements of bedding, faults and fractures.

For the glacial geological mapping, we collected rock samples to perform Surface Exposure Dating, by analyses on selected cosmogenic isotope.

On return from Antarctica, the activity comprised digitisation of the new cartographic data and elaboration of structural data. More analyses are planned when the rocks sampled during the expedition will be available.

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- Pocknall D.T., Chinn T.J., Skyes R., Skinner D.N.B. (1994) - Geology of the Convoy Range Area, southern Victoria Land, Antarctica. GNS Science Geological Map 11, 36 p. + 1 map.

## **Geodetic and photogrammetric survey of mud volcano in Santa Barbara village (Caltanissetta); implication of active tectonics**

Carnemolla, F.<sup>1</sup>, Brighenti, F.<sup>1</sup>, Messina, D.<sup>1</sup>, Lupo, M.<sup>1</sup>, Barreca, G.<sup>1</sup>, Monaco, C. & De Guidi, G.<sup>1</sup>

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**Keywords:** Mud Volcano, Geodesy, Morphometry, Active Tectonics, Monitoring.

The Santa Barbara mud volcano field is located in central Sicily, along the accretionary wedge forming the Sicilian-Maghrebian fold-and-thrust belt. It is constituted by Neogene-Early Pleistocene deposits that were progressively shortened and displaced during the late Miocene to Pleistocene (Monaco & Tortorici, 1996; Monaco & De Guidi, 2006;)

The “Maccalube” of Santa Barbara focus of attention after the paroxysm event occurred in August 2008, when a volume of 10000 m<sup>3</sup> of mud, covering an area of 12000 m<sup>2</sup> with a thickness of 3,5 m (Madonia et al. 2011), was ejected in few minutes. The paroxysm was preceded by an intense ground fracturing, with displacement spanning from few centimetres up to one meter, which involved many residential building (Dipartimento della Protezione Civile, 2008).

With the aim of understand what trigger paroxysm event (crustal and/or superficial stress field, overpressure of fluids) and to set up a valid geological model able to reduce the geological risk of the urban area, a multidisciplinary study was performed. Workflow has included studies on active (morphometry) and ground deformation, (IGM 95 geodetic benchmark) seismic profiles (Catalano et al., 2013), and epicentres of earthquakes occurred in central Sicily (Carnemolla, 2017). Since October 2016, we started monitoring the evolution of Santa Barbara active mud volcano through the installation of a GNSS network along the borders of the area covered by the materials ejected during the paroxysm of 2008. Geodetic measurements were also accompanied by photogrammetric surveys through an Unmanned Aerial Vehicle (UAV) to monitoring the most dangerous area and to obtain high-resolution DEM. Photogrammetric data and GNSS measuring were acquired during seven measurement campaigns (October 2016 - April 2018) and after compared each other to achieve information about ground motion and get the best 3D model of the mud volcano.

### **Actually**

The GNSS results show as expected that the mud volcano is affected by a radial movement in the order of one centimetre. Conversely, the photogrammetric data showed a more important vertical deformation in the vent area characterized by one order of magnitude more than the GNSS data. In particular, we observe a constant vertical movement in the central and northern sector of the vent area, that has been interpreted as a first and fast inflection phase, followed by a slower phase of inflection.

This study can contribute to evaluate if mud volcano activity along the Sicilian-Maghrebian fold-and-thrust belt (e.g. Aragona, S. Barbara and S. Biagio) are just related to independent overpressure fluids phenomena and/or by NNW-SSE compressive regional stress field (Bonini, 2007; Bonini, 2012;) (Tortorici et al., 2014).



## Monte Corchia: an example of 3D modelling with geology and karst system

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*Key words:* Mount Corchia, Apuan Alps geology, Karst system.

Mt. Corchia karst system is one of the most important and famous caves in Europe, with spatial length of about 60 km and depth of 1197 m, furthermore its three-dimensional geology architecture is very complicated due to polyphase nature of Tertiary tectonic deformations in the Apuan Alps area. We present for the first time the Monte Corchia 3D model of geology and caves.

The goal of this study is the realization of a three-dimensional underground model, taking into account both geological and speleological information. We will evaluate possible correlation between tectonic evolution and development of karst system and future prospective of marble excavation in this area, where we find one of the higher altitude marble quarry of the Apuan Alps, few hundred of meters near the karst system.

Caves orientation, position and underground development was considered in fact a priority in this study, because only a geological model would not be enough to estimate marble formation volume as well as a correct indication for future mining activities.

The Mt. Corchia 3D model evidenced the strongly geological control in the development of karst system. However the boundary between marbles and dolomites does not seem to represent an important geological horizon to the development of the caves. Further in the 3D model we can see the correlation between the volume of the geological formation (Marmi a Megalodontidi and Breccie di Seravezza Fm., Marble Fm. and Selcifero Fm.) and the percentage of spatial development of Corchia caves in each formation.

Here we present the preliminary results: a geological model, built on the basis of Prof. Marco Meccheri's geological surveys (University of Siena), carried out between 1980 and 2000, integrated with the 3d model of Mount Corchia karst system, using data collected in a century of exploration by speleologists.

## Numerical modeling of stress amplification and seismic faulting at lower crustal conditions

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*keywords:* lower crust; pseudotachylites; earthquake; pressure; finite differences.

Most of the crustal seismicity is localized in the first 10-15 km, above the brittle-ductile transition of quartz ( $T < 300\text{-}350^\circ\text{C}$ ), whereas at higher temperature and confining pressure deformation is believed to be essentially viscous and aseismic. Yet, the observation of deep earthquakes (40-80 km depth) and exhumed pseudotachylites formed at  $P > 1.0$  GPa argue for an elasto-plastic behavior of the lower crust, at least transiently. Frictional slip of dry and mechanically strong plagioclase-rich rocks at high confining pressure requires the build-up of differential stress exceeding 2 GPa, extremely localized weakening, or both. Theoretical considerations and experimental evidences suggest that shear heating, grain-size reduction, fluid pressurization, or a combination of both, can localize deformation. On the other hand, the top-down shift of aftershocks after large earthquakes indicates that stress pulses occasionally penetrate down to mid-crustal depths from the base of the seismogenic layer (Jamtveit et al., 2018). However, both the efficiency of weakening and the propagation of transient stress pulses in the lower crust remain controversial. In this contribution, we present a set of thermo-mechanical numerical experiments that simulate the deformation of a compositionally heterogeneous crust composed of inclusions and matrix with variable rheological contrast. The experiments have been performed using an elasto-visco-plastic 2D finite difference code based on a marker-in-cell algorithm, using boundary conditions that fit the typical lower crustal settings ( $T$  700 - 1000 °C,  $P$  1.0 - 1.5 GPa,  $v_x = 0.1$  - 0.5 cm/y). As a general outcome, the results show a consistent partitioning of the stress components between compositionally different domains of the shear zone, and within the strongest inclusions themselves. Another interesting feature shown by most experiments is the development of both negative and positive deviations from the lithostatic pressure within the strongest inclusions. Shear stress and pressure work in an additive way and have distinctive, non-overlapping patterns that depends on the geometry and composition of the rocks. The combination of underpressure domains and local peak shear stress in lower-crustal shear zones provide an explanation for the seismic behavior of the lower crust.

### References:

Jamtveit, B., Ben-Zion, Y., Renard, F., Austreim, H. (2018) - Earthquake-induced transformation of the lower crust. *Nature*, 556, 487-491.

## Ordovician tectonics in SE Sardinia: insights into geodynamic setting and paleogeography

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**Keywords:** Sardinic Phase, Gondwana, structural analysis, Qaidam Ocean, Rheic Ocean.

The Paleozoic metamorphic basement of Sardinia belongs to a segment of the southern European Variscan belt and consists of three main structural domains that are, from NE to SW: i) a medium to high grade metamorphic inner zone; ii) a green-schist facies nappe zone, subdivided into internal and external nappes, and iii) an anchimetamorphic thrust-and-fold belt foreland. Each Variscan domain shows clear evidences of Ordovician tectonic instability, ascribed to the Sardinic Phase, although the related deformation style and geodynamic setting are far from being fully understood.

The stratigraphic succession of the tectonic units stacked in the external nappe zone is made up of a Cambrian-Lower Ordovician siliciclastic succession unconformably sealed by a Middle Ordovician calc-alkaline volcano-sedimentary complex in turn covered by an Upper Ordovician-lower Carboniferous sequence.

Geological mapping and structural analysis carried out in the Sarrabus Unit, where the Variscan imprint is less penetrative as it is the shallowest unit of the external nappe stack, show that the angular unconformity (Sardinic unconformity) at the base of the Middle Ordovician volcano-sedimentary complex is due to a folding event affecting only the Cambrian-Lower Ordovician succession. These folds have overturned limbs and lack axial plane foliation, testifying that their development occurred at shallow crustal structural levels. Furthermore, no older crust is involved in the pre-Middle Ordovician deformation, suggesting a thin-skinned tectonic.

These features do not fit completely the Andean model proposed for the Ordovician tectonics in Sardinia, according to which the foreland, the external nappes and the internal nappes are the back-arc, arc and fore-arc, respectively. The characteristics of non-collisional orogens, such as strong uplift, lower crust exhumation, thick-skinned tectonics and volcanic arc on the crystalline basement, lack in SE Sardinia. Alternative geodynamic scenarios consistent with field observation could be an oblique plate convergence, an erosive subduction zone or an Alaskan-type subduction-accretion orogeny.

Paleogeographic reconstructions of the northern Gondwana margin in Ordovician times conflict each other, being Sardinia located sometimes in extensional setting, close to the opening up Rheic Ocean, sometimes in convergent setting, where the Qaidam Ocean was subducting under the South China terrane. Furthermore, major differences in the sedimentary source, stratigraphic succession, bio-province of faunas and magmatism occurrence between the foreland and nappe zone suggest that they belonged to different paleogeographic domains during early Paleozoic. Accordingly, the present-day Sardinian basement was amalgamated only during the Variscan Orogeny, and cannot longer be considered as a whole crustal block since Cambrian time as published reconstructions propose.

## **Modino, Cervarola, Tuscan Nappe and metamorphic units, relationships and tectonic evolution in the Emilia-Tuscany Northern Apennines.**

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*Keywords:* Northern Apennine, tectonics, low-angle normal faulting, exhumation.

Structural and biostratigraphic work in the Alpi Apuane, Cerreto- Ligonchio, Abetone-M. Cimone and upper Val di Lima areas allow to reinterpret some of the major tectonic lineaments and the stratigraphic-tectonic setting of the northern Apennine and to set some constraints for the tectonic evolution of this sector of the chain.

In the Alpi Apuane area detailed investigations in the central part of the metamorphic units allow to reconstruct a complex uplift history with superposition of different generation of normal and strike-slip faults. Most of these faults accommodate only minor displacements but have strong geomorphological evidence and play a key role in development of microstructures in marble rocks. The normal faults that now border the Alpi Apuane metamorphic complex are only responsible for the recent (still active) uplift of the region, but the main extensional event in the area is related with an older top-NE main regional low-angle normal fault that developed a thick cataclasite ("Calcare cavernoso" Auctt.) and led to unroofing and uplift of the metamorphic rocks. This low-angle normal fault is later crosscut by the high-angle normal faults that now border the metamorphic complex. This main low-angle normal faulting event is also responsible for development of cataclastic rocks at the base of the Tuscan nappe in the Lerici - San Terenzo - Punta Bianca area and for development of cataclasites in the Cerreto area, with clasts and slivers of medium grade metamorphic rocks embedded in Triassic dolomites and evaporites. This major low-angle normal fault represents therefore the basis of the Tuscan Nappe in the Alpi Apuane - La Spezia area and is the roof contact in the complex tectonic structure of the Cerreto area.

## **Deformational structures in Paleozoic sandstones of the Transantarctic Mountains: glacial vs tectonic origin**

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*Keywords:* glaciotectionism, thrust-sheet, tillite, Paleozoic, Transantarctic Mountains.

The Transantarctic Mountains (TAM), a 3000 km long mountain chain crossing the Antarctica, show a sedimentary cover (max 2.5 km thick), mainly formed of fluvial sandstone, with minor mudstone, gravel and coal, resting unconformably on the crystalline basement of the Ross Orogen (Barrett, 1991; Stump, 1995). This sedimentary succession, called Beacon Supergroup, is divided in two groups, which are the Taylor Group of Devonian age and the above lying Victoria Group of Permian to Early Jurassic age. Their subdivision is emphasized by a major erosional surface (Maya surface), and by the occurrence at the base of the Victoria Group of a tillite horizon referable to the Late Paleozoic Ice Age (LPIA, late Carboniferous (?) - early Permian, see in Barrett, 1991; Isbell et al., 2008; Cornamusini et al., 2017). This tillite horizon shows differentiate thickness along the TAM, built by a glacial succession formed of diamictite, mudstone with dropstone, sandstone and rare limestone beds and sometimes by a postglacial succession formed of mudstone, conglomerate and sandstone beds. The diamictite represents the most typical glacial deposit, showing massive and stratified lithofacies.

Some outcrops of this diamictite/tillite horizon show a complex stratigraphic architecture and deformational structures, as at Kennar Valley in the Beacon Heights and particularly evident are at Mount Ritchie (Warren Range) (Isbell, 2010). Here we have examined preliminarily the structures of this latter and remote outcrop. There, we recognize a deformed diamictite enclosing sandstone disrupted beds showing a chaotic texture, lying on to deformed sandstone beds. The diamictite with associated conglomerate on top is delimited upwards by the horizontal lying Permian sandstone beds of the Victoria Group. The deformational structures affecting the below sandstones beds of the ice substrata, show a complex imbricate stacking pattern with reverse and normal faults, sigmoidal shape thrust sheets and folds, involving an horizon some tens of meters thick. Collapsing and pop-up structures have been also recognized, whereas the above diamictite and disrupted sandstone beds lay horizontally and are also partially enclosed between the thrusts.

This typology of structures have been widely showed in glacial settings (Croot, 1987; Van der Wateren, 2002), due to the pushing and loading of the advancing glacial front on to unlithified deposits, which result to be deformed as thin-skinned thrust sheets. This interpretation has been also proposed by Isbell (2010) for the TAM outcrops, particularly at Mt. Ritchie.

Such structures are common affecting unlithified deposits as coeval glacial diamictites, but in our opinion they are unlikely affecting rocks, due to the ice dynamic and deformational strength. Furthermore, we think that the wide time-gap between the inferred Devonian age of the substrata sandstones and the Permian age of the tillite, prevents to have unlithified substrata deposit during the glacial event.

Following this reasoning, two explanations are identifiable for the deformational structures: i) they formed during a tectonic phase marking the limit between the two groups, interesting glacial and preglacial deposits; but an early Permian phase has been never identified in the TAM; ii) the below lying and deformed sandstone beds are not ascribable to the Devonian Taylor Group, but could be coeval with the glacial event (Early Permian) to represent an ice retreat pulse during waxing-waning ice masses of the multiphase LPIA.



## **Relationships between tectonics and sedimentation in the foredeep system of the Tuscany-Emilia Apennines through new stratigraphic data**

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**Keywords:** tectonics and sedimentation, nannofossil biostratigraphy, foredeep basin, Oligocene-Miocene, Northern Apennines

The Oligocene-Miocene turbidite successions of the Emilia-Tuscany Apennines represent one of the most intriguing topic of the Northern Apennines (NA), due to the complex relationships between tectonics and sedimentation in a migrating thrust wedge - foredeep system, to the not-well constrained differences between orogenic landslides (olistostrome) vs. tectonic chaotic complexes, to the significance of the associated marly deposits, to the emplacement timing and modalities of synsedimentary thrust sheets.

In order to achieve some key points to this articulated framework, we have contributed with field-mapping and stratigraphic data on selected marly-turbidite sections of the most critical areas of this sector of NA, which are: Mt. Modino, Civago-Torre degli Amorotti, Gazzano, Gova, Mt. Cimone, Ozola-Ligonchio, Cerreto Pass, Pracchiola, Libro Aperto-Cima Tauffi sections. All these involve some of the most known and not well constrained turbidite units of the NA, as the Mt. Modino Sandstones, the Mt. Cervarola Sandstones and the Gova Sandstones, and the associated marly units as Marmoreto and Civago marlstone fms. These last are also massively involved in highly deformed stacks within chaoticized tectonic units and slices, particularly in the Sestola-Vidiciatico Unit.

Our contribute on these sections regard a review of the geological and geometrical field-relationships with particular focus on biostratigraphic new data concerning nannofossil associations, allowing to redefine their age model. All this accompanied by a check for the compositional-petrographic data of the sandstone lithologies, has allowed to insert each section in a coherent basin-chain setting, obtaining an evolutionary model of the chain-foredeep of the NA during the late Oligocene-early Miocene. The main conclusive remark is the consolidation of the eastward migrating depositional system model, where the foredeep basin, split in several minor sub-basins, due to the pulsating thrusts of the advancing orogenic wedge was structured through two main stages. A first stage during the Chattian-Aquitainian with the development of partially different inner turbidite systems (Mt. Modino Sandstones in a frontal thrust-top basin, Macigno, Torre degli Amorotti System of the Mt. Cervarola Sandstones, Gova Sandstones, etc.) and a second stage developing the wide Mt. Cervarola Sandstone Complex. The two stages result to be separated by the tectonic Tuscan Phase with a deformative acme during the earliest Burdigalian, leading to the development of the Sestola-Vidiciatico Unit and the following involvement of all the sequences in the unit stack.

## **Aborted propagation of the Ethiopian rift in the Turkana depression and implications for the interaction with the Kenyan rift**

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**Keywords:** continental rifting, rift interaction, East African Rift, Turkana depression.

Continental rift systems commonly form by growth of isolated rift segments that progressively evolve into continuous zones of deformation. Propagation and interaction between adjacent rift segments are important features of rifting (Faulds and Varga, 1998), possibly controlling rift morphology at breakup with implications for mid-ocean ridge segmentation (e.g., Taylor et al., 2009). However, despite its importance, the complex, three-dimensional evolution of rift linkage is poorly documented in active continental rifts and difficult to reconstruct from old conjugate margins.

In this work we present geological-structural, geochemical and geochronological data from the poorly documented Ririba rift (South Ethiopia) that reveals how two major sectors of the East African rift, the Kenyan and Ethiopian rifts, interact in the Turkana depression. Our data indicate that the roughly N-S-trending Ririba rift formed from the southward propagation of the Ethiopian rift during the Pliocene. However, in striking contrast with previous suggestions (Ebinger et al., 2000; Bonini et al., 2005), our analysis indicates that this propagation was short-lived and aborted at the beginning of the Pleistocene, when rift-related deformation ceased.

Integration of seismicity analysis with new numerical models of rift interaction indicates that abandonment of laterally offset and overlapping tips of the Ethiopian and Kenyan rifts resulted from progressive focusing of the tectonic and magmatic activity into an oblique, thoroughgoing rift zone, which directly connects the rift sectors. Comparison of the results of numerical modelling with seismicity data suggests that these sectors link by near pure extension without forming transfer faults with significant strike-slip deformation.

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## Fault-volcano interaction in extensional areas

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### Keywords:

Areas undergoing pure extension are typically characterized by formation of faults and fractures orthogonal to the maximum principal stress. In such areas, the presence of a volcano and its magmatic system can perturb the local stress field, leading to changes in the faulting magnitude and attitude. We analyzed the interaction of tectonic stresses with volcanic edifices and magmatic intrusions in areas experiencing distributed extension. To this aim, we run a set of analogue models deformed by using a basal rubber sheet, whose stretching allowed inducing a progressive, diffuse extension to models. This modeling approach improved previous experimental set-ups, in which extension was obtained by motion of rigid base-plates inducing a basal velocity discontinuity that may result in an unnatural distribution of stresses. The models consisted of a brittle-ductile system, with a volcanic edifice simulated on their surface; in some experiments, a small cylindrical pocket of fluid material was introduced in the brittle layer to simulate an intrusive body or magma chamber.

We found that the presence of a volcano and/or an intrusive body locally modifies the fault pattern. The volcano load favors the formation of radial faults, whereas the presence of an intrusion leads to concentric faults around the intrusive body. The combination of both creates both types of faulting, how it is seen in natural examples. Our results indicate that volcanic edifices have a stronger influence on the fault pattern with respect than the presence of intrusions. Experimental results are compared with some natural cases from the East African Rift System.

## Finite strain tensor estimation from elliptical markers: the problem of pre-oriented and random oriented ellipses based statistics

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**Keywords:** Pre-oriented elliptical markers, Finite strain estimation, Statistical analysis, Underdetermined inversion problem.

Main challenge in finite strain inversion analysis consists in dealing with statistics based on preferentially oriented elliptical strain markers; most of finite strain estimation methods up to now provided in literature (e.g. Yamaji, 2013; Vitale 2014; and references therein) are based on two main hypotheses: (i) elliptical markers are assumed randomly (uniformly) oriented before strain occurs, (ii) the problem is geometrically determined in terms of two parameters of strain tensor: ellipticity  $R_s$  and angle  $\theta$  between stretching direction and a reference axis. Some methods which consider the hypothesis of pre-oriented markers have been proposed in literature (e.g. Elliott, 1970; Dunnet and Siddans, 1971; Wheeler, 1986, Yamaji, 2005), nevertheless these show some weak point mainly related to very restrictive hypotheses about original system geometry, whose validity is generally uncertain and/or hard to be assessed.

We have carried out a theoretical investigation about the problem of finite strain inversion based on elliptical strain markers which proves that, in the case of pre-oriented markers and under general hypotheses, statistical analysis cannot provide results in terms of the mentioned variables  $R_s$  and angle  $\theta$ , whereas only the ratio  $r = d_{12}/d_{22}$  and product  $p = d_{21} d_{22}$  - where  $d_{ij}$  denote strain tensor entries - can be calculated.

Namely, it has been assessed that, under hypothesis of pre-oriented markers, all strain tensors showing ratio  $r^* = d_{12}/d_{22}$  and product  $p^* = d_{21} d_{22}$  equal to those of the true strain matrix  $\mathbf{D}$  (i.e. the sought solution), provide retro-deformed systems showing suitable configurations; these values can be evaluated by minimization of an appropriate object function. We point out here that infinite couples of values ( $R_s, \theta$ ) are associated to the same  $r^*$  and  $p^*$  values - i.e. the strain ellipse remains indefinite - and, so, the inversion problem needs to be differently afforded than the classical problem based on hypothesis of originally random oriented markers.

The reached conclusions show interesting implications when further field data are involved in inversion analysis, such as bedding orientation and/or deformed fossils, as these can make or not the inversion problem fully determined (i.e. for which all components of the strain tensor can be evaluated), according to the adopted assumption about original marker geometry (random oriented or pre-oriented).

Below the variables which can be calculated according to several scenarios of available data and assumed hypotheses, are summarized.

- Hypothesis of pre-oriented markers:  
determined parameters from marker statistics: **2 of 3** ( $r, p$ )  
with bedding trace: improved calculus quickness and convergence  
with fossil: **3** determined parameters (fully determined problem)
- Hypothesis of random oriented markers:  
determined parameters: **2 of 3** ( $R_s, \theta$ )  
with bedding trace: **3** determined parameters (fully determined problem)  
with fossil: allows to test the basic hypothesis of random orientation

## Mud volcano eruptions induced by the 2016-2017 Central Italy seismic sequence

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**Keywords:** Mud volcanoes, Central Italy seismic sequence, Seismic triggering, Static stress, Dynamic stress.

On 24<sup>th</sup> August 2016 a seismic event ( $M_w$  6.0) stroke near Amatrice, initiating the long, and still ongoing in 2018, Central Italy seismic sequence. The sequence was characterized by medium-to-high magnitude earthquakes, with several large seismic events (nine of which with a  $M_w \geq 5$ ), and about 74.000 seismic events registered after 1 year of activity. A second major seismic event, the largest of the sequence, was the  $M_w$  6.5 30 October 2016 earthquake, that hit the area near Norcia. Furthermore, during January 2017 four  $M_w \geq 5$  stroke the area of Montereale-Capitignano-Campotosto ( $M_{wMAX} = 5.5$  on 18<sup>th</sup> January 2017). After these major earthquakes, 17 mud volcanoes erupted around Monteleone di Fermo and S. Vittoria in Matenano villages (Marche region). Most of these mud volcanoes were already existing in the area and were well known, while some of them were not present before the earthquakes. Interestingly, mud volcano eruptions in the Monteleone di Fermo area occurred a few hours to a few days after the main earthquakes. This intriguing temporal correlation suggests a possible seismic triggering. We aimed to investigate this possibility, and therefore we evaluated the variation of peak ground velocity and dynamic stress during the three largest earthquakes (i.e. the  $M_w$  6.0 Amatrice, the  $M_w$  6.5 Norcia and the  $M_w$  5.5 Montereale-Capitignano-Campotosto earthquakes). Furthermore, we evaluated the static stress changes in order to assess the potential influence of normal stress changes on the feeder system (i.e. a fracture array exploited by fluids migrating upwards from the subsurface reservoir/s) of the activated mud volcanoes. We suggest a correlation with dynamic stresses, which showed values large enough to trigger the mud volcano eruptions, whereas static stress changes are negligible or negative (with negative values up to -0.44 bar, clamping the feeder dykes and discouraging the eruption). We conclude that seismic shaking (up to ~3.9 bar during Norcia earthquake) is the dominant triggering cause for these eruptions. As a confirmation, we evaluated the response ratio of the mud volcanoes as a function of the dynamic stress. This ratio increases exponentially with peak dynamic stress varying from <10% for peak dynamic stress >0.3 bar to >50% for peak dynamic stress >2 bar, thereby indicating a straightforward statistical link between earthquake shaking and mud volcano activity.



## **Oroclinal bending, strike-slip tectonics and block rotations in central and north Iran**

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*Keywords:* Iran, strike-slip tectonics, paleomagnetism, Arabia-Eurasia convergence.

In Central and North Iran different deformation patterns are observed in high-topography mountain belts and flat-lying desert areas, the former characterized by curved shape, active folding and thrusting distributed over a wide area and the latter by large strike-slip faults, which bound almost rigid crustal blocks. These strike-slip faults show different orientation and kinematics: NE-SW to E-W oriented left-lateral faults characterize the tectonic boundary between Central Iran and the Alborz Mts., whereas N-S right-lateral strike-slip faults prevail along the tectonic boundary between the Yazd, Tabas and Lut blocks. Vertical axis rotations of fault-bounded crustal-blocks have been considered as a possible mechanism to explain the active pattern of deformation in several regions of Iran.

In order to define the pattern of vertical axis rotations associated to the Arabia-Eurasia shortening, new paleomagnetic data from Miocene units from the different tectonic blocks of Central Iran and from the curved orogenic belts from northeastern Iran (Central and Eastern Alborz Mts.) have been collected. In north-eastern Iran a general correspondence between the orientation of the different sectors of the curved orogen which comprises the Central and Eastern Alborz Mts. and the trend of paleomagnetic rotations was observed. This correspondence suggests that oroclinal bending is a valuable mechanism to explain the present-day curvature of these orogenic belts. In Central Iran, CCW paleomagnetic rotations have been measured in the Yazd and Tabas block, which are characterized by N-S to NNW-SSE oriented right-lateral strike-slip faults, whereas CW paleomagnetic rotations have been measured in areas where E-W oriented left-lateral strike-slip faults are predominant (e.g. Ferdows area in the Lut block) and Torud and Jamdag area north of the Great Kavir fault. Accordingly, vertical axis rotations could have accommodated a significant portion of N-S shortening related to the Arabia-Eurasia convergence during the Tertiary.

## No-contact field survey techniques for structural analysis

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**Keyword:** Geological map, Digital survey, 3D outcrops, UAV, SfM

In the last years, the geological digital mapping reaches a mature technology, widely available that improve the efficiency in the field survey, where the knowledge of geological structures and their topological relationships are important. Since the first geological maps, the representation of the 3D real world in a 2D flat fixed map had represented a strong limitation to the dissemination of geological data. To understand the strange patterns and patches of different colors of a geological map remained for decades a privilege of geological insiders. The real life is in 3D and every day, there is a strongest demand for spatial data to the represent the real shape of the World. Today exists a mature digital technology to acquire data, changing the methods of mapping geological structures, shifting from a static to dynamics representation, continuous updatable, using different methodological approaches and sources of data at variable scales. In the digital millennium, the main contribute to the geological field survey derive from the GNSS (global navigation satellite system) geolocalization, probably the best geological tool after the compass. In the last decade, 3D virtual outcrops derived from the LIDAR (Light Detection and Ranging) technology, which is limited by the cost and by instrumentation required. The main step to the 3D world derive from the digital photography, which is not only recorded outcrop images at no practically cost but because it contains a huge amount of numerical information. These numerical data can be easily extract with the aid of the computer vision technology, where a new generation of algorithms like “Structure from Motion” or SfM developed in few software permit easily to obtain 3D spatial geolocalized clouds of data. Starting from few digital photos a 3D virtual outcrops can be built, making photogrammetry available to a growing number of Earth scientists. Most recently the flying platform systems ready-to-use, like small Unmanned Aerial Vehicles or UAVs, able to carry different type of payload including sensors and cameras, represent the final loop of this digital revolution. These UAVs use a flight control unit (FCU) able to process autonomous and remote navigations commands from the pilot, which get avionic data from one or more inertial measurement unit (IMU), magnetic compass and one or more GNSS receivers also with RTK (real time kinematic) capability. The combination with low altitude photos, both zenithal than oblique, permits to obtain easily georeferenced 3D point clouds with centimeters accuracy. Topography or DSM maps are the direct products, but the possibility to analyze spatial geological structures especially in hazardous or inaccessible areas, represent actually one of the important application. Starting from few examples, in the different structural contest from simple outcrops to complex coseismic ruptures patterns, the efficiency, precision and limits of these technologies and methodologies are discussed.

## Geological and structural characterization through gravimetric prospection of Giumentina Valley (Majella, Abruzzo, Italy)

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**Keywords:** Gravimetric Survey, Giumentina Valley, Majella.

In the archeological study of Giumentina Valley, near Caramanico Terme (Majella, Abruzzo, Italy), we performed a gravimetric survey with the aim of delineating the geological and structural settings. This is an ancient valley-basin which its riverbed was carved in Cenozoic limestone and has been filled with fluvial, lacustrine and slopes detrital sediments. Its geological history is closely connected to the evolution and the morphogenesis which affected the northern side of the Majella Massif in the last million years. In fact, the Giumentina Valley is a hanging valley originated as a consequence of paleogeographic variations that have led to the formation of lakes and marshes as well as the formation of endorheic karstic structures in some points of the abandoned riverbed.

In order to reconstruct the stratigraphic and structural settings along the valley we planned to carry out a gravimetry prospection. The studied area is about 3.3 km<sup>2</sup> and we carried out a gravimetric survey of 104 points by a rectangular grid mesh (175x240 m) and with random points in the area with karstic evidence. We measured some stations for the drift correction, using the base stations linked to each other.

For each station we repeated 4 measures in order to reduce the errors and to improve the accuracy of the data.

The processing of the data has been done with appropriate software by which we applied the tide correction and the drift correction. For the drift correction, we used three base stations connected to different zones and the base station of the whole survey.

We calculated the mean error of 0.003 mGal for each measurement and the error standard deviation of 0.007 mGal. The stations with an error higher than the mean value have not been considered in the processing.

For the processing of the data we applied the correction of the free air and Bouguer correction, which were calculated considering the acquired topographic measures and a density value of 2.3 g/cm<sup>3</sup>. The density parameter was calculated by the Nettleton method. In this method, the mean density value is calculated by the removal of the correlation between the observed gravity and the topography.

The last operation that we applied in the processing was the terrain correction using two digital elevation models (DEM) with different resolutions: one at 10 m and the other at 20 m. The data of the DEM were calculated from the data of Carta Tecnica Regionale with scale 1:5000 (CTR, sheet: 370013,370014).

The corrected data have been interpolated to obtain the Bouguer anomalies map and on this map we applied two algorithms to underline the shape of the gravimetric anomalies and the structural settings.

The map of the vertical gradient has been created by derivation along the Z axis. This operation increases the signal of the superficial sources and eliminates the contribution of the deep sources. The effect of this operation corresponds with a high pass filter.

The map of the maximum horizontal gradient has been created to underline the margins of the sources. The maximum values of the grid are in correspondence with the maximum slopes in the input grid. By combining these maximum values we delineated the margins of the sources.

By the analysis of the Bouguer anomalies maps, we highlighted four principal anomalies, some positives and some negatives.

Positive anomalies were in correspondence with the carbonate substratum. One of the negative anomalies was near to the clay-rich rocks and altered carbonate lithologies with evident dissolution signs.

## **NEOGENE 3D-structural architecture of the North-West Apennines: The role of the Low angle normal faults and basement thrusts**

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*Keywords:* tectonics, Northern Apennines, LANF.

The northern Apennines of Italy are a classical site for studying fundamental issues in tectonic studies, such as ophiolite formation and emplacement, kinematics of thrust wedges, role of in- and out-of-sequence thrusting, and of along strike segmentation, syn-orogenic versus post-orogenic extension, interplay between tectonics, erosion and sedimentation etc. Accordingly, the northern Apennines have been extensively studied since more than two centuries ago. Despite the huge amount of available data with different resolution, a 3D comprehensive regional view combining in a modern framework all available surface and subsurface information for contiguous sectors of the chain is still lacking. We performed such an attempt in the area framed between the Taro valley to the north and the northern termination of the Alpi Apuane to the south. The region includes the main morphostructural zones of the North-West Apennines from the Tyrrhenian coast (SSW of La Spezia), through the main topographic divide of the Apennines, up to the foothills range of the chain to the north. The area has been investigated through a multidisciplinary approach that integrated surface geological data, collected during the last two decades of structural and stratigraphic field works, and subsurface geological data. The construction of two regional NE-SW trending cross-sections (the Levante-Pontremoli-Parma to the north and the La Spezia- Sarzana-North Apuane-Cerreto to the south), intersected by a NW-SE trending Taro-Lunigiana-Alpi Apuane composite section, allowed us to illustrate (i) the role of out-of-sequence blind thrusting in the basement, (ii) the presence of low-angle normal faulting and its relationships with recent to active high-angle normal faulting. Both extensional and contractional systems have relevant implications for the tectonics of the northern Apennines as well as the seismotectonics of the studied region.

## **Analogue modeling of the deformation associated to shallow magma intrusions: hints on supercritical fluid flow**

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*Keywords:* analogue modeling, forced folding, supercritical, fluids, geothermal exploration, magma emplacement.

Magma emplacing at shallow crustal levels may cause significant deformation in the overlying country rock (i.e., forced folding, fracturing and faulting), both at a local and/or regional scale (e.g., Hansen and Cartwright, 2006; Jackson et al., 2013; Senger et al., 2015). To get insights into these processes, we investigated in the laboratory the development of forced folds and associated fracture/fault networks. An analogue magma, simulated by polyglycerols, was intruded into a sand pack representing the brittle crust. To test the effect of key parameters the model host rock thickness, the volumetric flux, and the velocity of magma injection for a constant volume of injected material have been systematically varied. The scaled analogue models reproduced different 3D deformation structures depending on the model parameters. However, all models support the observation that the emplacement of shallow magmatic bodies may result in the growth of dome-shaped forced folds, and associated development of tensional and compressional deformation in the host-rock. Downward propagating normal faults form to accommodate the uplift associated with the forced folding of the supra-intrusion overburden. These normal faults are generally characterized by a limited vertical throw, and affect only the outer, upper part of the broad dome and scarcely extend into depth. Conversely, upward-propagating reverse faults invariably crosscut the entire sand pack, propagating from the analogue magma up to the model surface. Model results also indicate that the presence of ductile weak layers embedded in the cover rocks could inhibit the up-ward propagation of these structures. On the basis of the modelling results, we suggest that the inward-dipping annular reverse faults are likely to significantly influence the distribution and migration of supercritical geothermal fluids near the edge of the magma intrusions. Although the models involve simplifications, these results provide useful hints for geothermal research, as fractures and faults associated with magma emplacement can significantly influence the distribution and migration of superhot geothermal fluids (Montanari et al., 2017). These structures can therefore be considered potential targets for geothermal and/or ore deposit exploration. In this perspective, the results of analogue models may provide useful geometric constraints for field work, numerical modeling, and particularly seismic interpretation, allowing production and a better understanding of integrated conceptual models concerning the circulation of supercritical fluids.

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## Analogue models of multiple magma emplacement, effects on the superficial deformation and lateral magma migration

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**Keywords:** analogue modeling, forced folding, lateral magma migration, fluids, geothermal exploration, magma emplacement.

To test the effect exerted by multiple magma emplacement on the deformation pattern, we have run analogue models with synchronous, as well as diachronous magma injection from different, aligned inlets. The distance between injection points, as well as the activation in time of injection points was varied for each model. Model set-up, materials and scaling are discussed in Montanari et al. 2017)

Our model results show how the position and activation in time of injection points (which reproduce multiple magma batches in nature) strongly influence model evolution. In the case of synchronous injection at different inlets, the intrusions and associated surface deformation were elongated. Forced folds and annular bounding reverse faults were quite elliptical, and with the main axis of the elongated dome trending sub-parallel to the direction of the magma input points. Model results also indicate that the injection from multiple aligned sources could reproduce the same features of systems associated with planar feeder dikes, thereby suggesting that caution should be taken when trying to infer the feeding areas on the basis of the deformation features observed at the surface or in seismic profiles. Diachronous injection from different injection points showed that the deformation observed at surface does not necessarily reflect the location and/or geometry of their feeders. Most notably, these experiments suggest that coeval magma injection from different sources favor the lateral migration of magma rather than the vertical growth, promoting the development of laterally interconnected intrusions.

Recently, some authors (Magee et al., 2014; Magee et al. 2016; Schofield et al., 2015) have suggested that, based on seismic reflection data analysis, interconnected sills and inclined sheets can facilitate the transport of magma over great vertical distances and laterally for large distances. Intrusions and volcanoes fed by sill complexes may thus be laterally offset significantly from the melt source. Our model results strongly support these findings, by reproducing in the laboratory a strong lateral magma migration, and suggesting a possible mechanism. The models also confirmed that lateral magma migration could take place with little or no accompanying surface deformation.

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## Tectonic evolution of the metamorphic core of the Himalayan belt

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**Keywords:** Himalaya, shear zone, exhumation, petrocronology.

The mid-crust is exposed in the Himalayan belt mainly in the Greater Himalayan Sequence (GHS) which stretches all over the 2400 km of length of the belt. A multidisciplinary approach, integrating geological mapping, structural analysis, petrology and geochronology allowed to better unravel the internal architecture of the GHS. It is characterized by several tectonic-metamorphic discontinuities at the regional scale with a top-to-the-S/SW sense of shear, the older one being active since ~ 40 Ma. The GHS is consequently divided in three main tectonic units exhumed progressively from the upper part to the lower one by top-to-the S/SW ductile shear zones, later involving the Lesser Himalayan Sequence (Montomoli et alii., 2013, 2015; Carosi et alii, 2018). The activity of the shear zones bounding the three units of the GHS lasted several Myr at the point to affect the metamorphic paths of the hanging wall and footwall rock which recorded maximum P-T condition in different times. The upper and the older shear zones in the GHS triggered the earlier exhumation of the uppermost part of the GHS allowing the upward migration of the melt subsequently produced in abundance in the upper part of the GHS at the time of activation of the HHD. Production of melt continued to upper structural levels where LP andalusite and cordierite bearing granites emplaced.

The timing of activation of shear zones from the deeper to the upper structural levels allow to propose an in-sequence shearing tectonic model for the exhumation of the GHS, further affected by out-of-sequence-thrusts.

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## **Tectonic inversion, positive and negative: a role for strike-slip deformations?**

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*Keywords:* Inversion tectonics, stress regime, strike-slip faulting, Somerset, Umbria-Marche Apennines

Interpretations of stress orientations, fluid pressures ( $P_f$ ) and deformation chronologies are keys to most structural analyses. Here, we link the changes in the magnitudes of stress axes with related changes in  $P_f$  to understand a common phase of strike-slip deformation between periods of regional extension and regional contraction.

Field data from an orogenic foreland and an orogenic belt (the Mesozoic rocks of southern England and the Umbria- Marche Apennines of Italy, respectively) indicate the following. Firstly, stress evolution during the tectonic cycle, between maximum compressive stress ( $\sigma_1$ ) being vertical during extension and least compressive stress ( $\sigma_3$ ) being vertical during contraction, can involve phases when the intermediate compressive stress ( $\sigma_2$ ) is vertical, promoting strike-slip deformation. Secondly, variations in the relative magnitudes of the stress axes are caused by variations in overburden and tectonic forces. Thirdly, overpressure can develop because of compaction during burial, and, as overburden is reduced during uplift and erosion, the vertical stress ( $\sigma_v$ ) reduces but fluid pressure ( $P_f$ ) remains approximately constant. Brittle deformation, including transient strike-slip faults, reverse-reactivated normal faults and normal-reactivated thrusts, is preferentially developed in overpressured areas because high  $P_f$  promotes faulting.

These field examples, from different tectonic settings, suggest such behaviour is common in areas that have undergone single as well as multiple inversion histories.

## **Buca della Vena mine: an example of polyphasic ore deformation in the world-class Tl district of Apuan Alps (Italy)**

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**Keywords:** geological mapping, polydeformed structures, ore deposit, Buca della Vena mine, Apuan Alps.

The Apuan Alps ore district (Tuscany, Italy) hosts several ore types that were exploited from Middle Age to the beginning of the '990, when mining activities definitely ceased. The volumetrically most important orebodies are located in the southern Apuan Alps and they mainly consist of pyrite  $\pm$  baryte  $\pm$  iron oxides. These orebodies were exploited by several mines along a ca. 10 km SW-NE discontinuous mineralized belt from Valdicastello Carducci, close to Pietrasanta, to Fornovolasco.

Several papers have investigated the geometry, petrography, and mineralogy of these ore deposits (e.g., Lattanzi et al., 1994 and references therein) but, with the end of the mining activity, also the scientific interest declined. However, the recent discovery Tl-sulfosalts assemblages as well as the high Tl content in pyrite ores (Biagioni et al., 2013), representing an environmental hazard, renewed the scientific interest for these ore deposits.

A detailed field and underground geological mapping of the Buca della Vena mine, which belongs to the group of pyrite  $\pm$  baryte  $\pm$  iron oxide ore deposits, was recently performed. Indeed, owing to the good exposures, this small mine likely represents the best locality for the investigation of the ore bodies and their host-rocks in southern Apuan Alps. This study reports a detailed geological-structural investigation performed from cartographic to micro-scale, showing that the actual configuration was acquired during Tertiary polyphasic deformation of a Permian-Triassic(?) proto-ore. The orebodies occur along the tectonic boundary between the Paleozoic basement and the Mesozoic carbonate cover and were later involved in isoclinal folds and late-stage folds with sub-horizontal axial plane. Finally, brittle faults dissected the orebodies and all the previous tectonic structures. The deformational features are emphasized by the strongly contrasting rheology of ores and host-rocks during Alpine metamorphic event.

The 3D reconstruction allows us to determine the tonnage of the Buca della Vena orebodies estimated in around 300000 t with a Tl-content of around 5.5 t (ore grade from D'Orazio et al., 2017).

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## The tectonometamorphic evolution of the Austroalpine units of the Eastern Alps in the frame of the early Alpine orogenesis

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**Keywords:** Eastern Alps, Cretaceous, pre-collisional deformation, HP metamorphism.

The record of the early, pre-collisional, stages of the Alpine orogenesis are chiefly recorded within the Austroalpine and Southalpine units of the Alps. In the Eastern Alps, HP metamorphism of late Cretaceous age is recorded in several units, referred to the Koralpe-Wolz nappe system (Schmid et al., 2004).

To the west of the Tauern Window, the above-mentioned nappe system is represented by the Texel unit. This unit is the structurally lowest element of the Austroalpine domain, made by, north of the Insubric Fault, the Texel, Scheneeburg and Ötztal-Stubai units.

The Ötztal-Stubai complex consists of a polymetamorphic basement and its autochthonous Permian-Mesozoic metasedimentary cover, made by a metaconglomerate (Basal Conglomerate *Auct.*) and calcareous schists and marbles. In the Schneeberg and Tribulaun areas (BZ, NE Italy) the basement-cover non-conformity is still roughly preserved. Structural investigations across such discontinuity serve to reconstruct the Alpine deformation history. Mafic to intermediate dikes that cut across the basement regional foliation but do not intrude the post-Variscan cover provide additional structural constraints. Alpine deformation resulted in a penetrative foliation in the sedimentary cover coupled with a stretching lineation due to a top-to-W (NW) shearing. P-T estimates constrain metamorphism of Alpine age in metaconglomerates and dikes at 450-500°C and 0.8-1.0 GPa. <sup>40</sup>Ar-<sup>39</sup>Ar dating of micas within conglomerates and recrystallized biotite in dikes provide ages of about 85 Ma. These data are very close to the age of the eclogitic metamorphism in the Texel unit (Habler et al., 2006; Zanchetta et al., 2013) and the HP amphibolite facies metamorphism in the Schneeberg complex. All together these data suggest that metamorphic peak conditions were experienced contemporaneously by the three units when they were at different crustal levels. During exhumation, the HP Texel unit was first coupled with the Schneeberg unit (the two units show a common evolution since the amphibolite facies re-equilibration of the Texel eclogites) and then the Schneeberg-Texel was brought in contact with the Ötztal basement and cover at shallow crustal level.

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## Early Permian synsedimentary tectonics in the central Southern Alps

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**Keywords:** Early Permian, extension, synsedimentary tectonics, liquefaction.

The Lower Permian deposits of the central Southern Alps consist of a thick succession of volcanic units passing up section to alluvial and lacustrine sediments (Laghi Gemelli Group) deposited in an arid environment (Cadel et alii, 1996; Berra et alii, 2016). Evidence of a strong synsedimentary tectonics was recognized along the Orobic watershed of the Brembana Valley, within the upper portion of the succession in the terrigenous deposits of the Aga Conglomerate and the Pizzo del Diavolo Formation. Perfectly exposed outcrops document the geometrical relationships between low-angle normal faults and high-angle synsedimentary faults, which were active during the deposition of the base of these units. High-angle normal faults displace the base of the Aga Conglomerate and Pizzo del Diavolo slates and sandstone, causing marked facies variations and thickness increase.

An incredible record of synsedimentary mesoscopic faults crops out along the western slope of Cima Aga at an elevation of more than 2,500 m providing a perfect exposure of the structures. Mesoscopic observations, including the measurement of more than 250 fault planes with their displacements, were completed through photogrammetric techniques, which allowed for the 3d reconstruction of the most significant outcrops. Most of the mesoscopic faults show “*Andersonian*” features accompanied by liquefaction structures as flames, balls and pillows, sand dikes and other hydroplastic deformations. Coarse-grained breccias accompany the largest faults, which show variable features ranging from perfectly planar to listric planes.

All these observations, together with the occurrence of low-angle normal faults, point to a tectonic regime dominated by pure extension producing half-graben dominated by an interplay among low- and high-angle normal faults. Based on these lines of evidence, we suggest that the deposition of the Lower Permian units was here dominated by an extensional regime rather than by a transtensional one, as previously suggested by most of the authors.

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## Rheological profiles in the epicentral area of the 2014-2015 Ionian Islands seismic sequences: implications for seismogenesis

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**Keywords:** brittle and ductile layers, Western Greece, seismic events.

Two different rheological profiles have been realised in the region of Cephalonia and Lefkada islands (Western Greece), with the aim of comparing the vertical strength envelopes with the actual depth distribution of the hypocentres of the seismic events related to the sequences occurred in 2014 (Cephalonia) and 2015 (Lefkada). Rheological profiles represent a first indication for identifying the brittle, potentially seismogenic layers and the ductile, aseismic ones, which deform mainly through plastic creep. Accordingly, aftershocks depth distribution should almost coincide with the extension of the brittle layer, while the seismogenic nucleation should cease in correspondance of the ductilely deforming regions. The strength envelopes for Cephalonia and Lefkada have been realised using a Matlab code, which iteratively computes (along depth) the minimum strength between the frictional sliding (brittle layer) behaviour and the power-law creep representing the ductile behaviour. The values for the input parameters of the governing rheological equations have been selected on the basis of the available literature and geological/tectonic constraints. In particular, the two test sites basically differ in terms of i) thickness of the sedimentary (mostly carbonatic) cover, which is 2 km thicker in Lefkada (Makris *et al.*, 2013); ii) tectonic regime, which is transpressive for both sites, but tends to exhibit a slight increase of the thrust component in correspondence of the Lefkada segment of the Cephalonia Transform Fault (Louvari *et al.*, 1999). The resulting rheological profiles show a slightly deeper BDT for the Cephalonia test sites (~17.5 km) with respect to the Lefkada one (~16 km). Such a result is consistent with the depth distribution of the seismic events for the 2014 Cephalonia and 2015 Lefkada sequences (see Karastathis *et al.*, 2015; Ganas *et al.*, 2016 among others), which are indeed characterised by a shallowing trend of the seismicity cutoff depth in a SSW-NNE direction from Cephalonia (max hypocenters at 18 km) towards Lefkada (max 15-15.5 km).

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