Young Researchers in Structural Geology and Tectonics

YORSGET Montgenevre, France 1-6 July 2018

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TALKS

The internal structure and development of faults cutting coal bearing stratigraphy

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The impact of mechanical stratigraphy on fault development is well known, however, how coal, which is a naturally fractured rock due to the presence of the coal cleat, impacts fault development remains poorly understood. This work aims to understand the internal structure of fault zones cutting coal bearing stratigraphy, how such fault zones develop as displacement increases, and what impact coal has on the strength of the sequence. Detailed fieldwork on normal and strike-slip faults of varying displacements (cm's to 10's of m) was undertaken in order to develop models of how faults develop when coal is present in the stratigraphy.

The architecture of faults at two field sights have been studied (a section of the Northumberland Coast and Spireslack Surface Coal Mine (SCM), Aryshire. The Northumberland site (just north of St. Mary's Lighthouse) is 4 km north of the Ninety Fathoms fault, which forms the southern boundary of the Northumberland Trough, and is cut by numerous strike- and dip-slip faults relating to this major structure. The Stratigraphy consists of cycles of sandstone, siltstone, shale and thin coals (up to 1 – 1.5 m) of Westphalian B Coal measures. Spireslack SCM, situated in the south west of the Midland Valley of Scotland, is a roughly 1 km long, 80 m deep, NE-SW trending void that cuts into the southerly dipping, northern limb, of the Muirkirk syncline. The syncline is cut by several sinistral strike-slip faults (offsets from cms to 120 m). Lithologies at Spireslack SCM consist of limestones (Housie Limestones), sandstones, siltstones, shale, seat earths and thin coals (<2.5 m) of the Visian aged Limestone Coal formation.

Both sites provide excellent outcrops to investigate the internal structure of fault zones along strike and in cross section. The range in offsets enables models to be produced on how fault architecture develops with increasing displacement. Both sites have experienced predominantly strike-slip tectonics which enables direct comparison to be made when creating schematic models. One major difference between sites is the relative dip of bedding and faults (beds are sub-horizontal in Northumberland and 30-40° in Spireslack SCM), which effects fault development.

Whether a fault is self-juxtaposed (beds do not move past each other) or not (offset moves the stratigraphy past multiple beds) impacts the complexity of the fault zone. Complexity increases dramatically once beds are moved past different lithologies, especially when passing less competent layers (e.g. shale). The properties of the whole sequence, not just the coal, needs to be considered as different lithologies deform in very different ways. Less competent layers (e.g. shale) often cause bed rotations and splays to develop, increasing the number of fault strands cutting through coal seams. Faults are non-planar, however, lens development is more prevalent in Northumberland, with folding of weak layers more prevalent at Spireslack SCM. These findings have important implications for fault growth in strike slip settings along with many industry applications (e.g. Coal bed methane, Mine safety, Subtle gas field development in the North Sea and Geothermal energy).

Micromechanical investigation of olivine grain boundaries

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Long- term tectonic deformation is controlled by the rheology of the dominant minerals in the upper mantle. In this context a key question is the strength of the lithosphere, which can be approached both experimentally and numerically. Experimental studies focusing on the strength of olivine under low temperature and high stress exhibit little consistency and disagree with numerical predictions and inferences from geophysical data. Thus, it is difficult to draw any robust conclusion about the strength of the lithosphere from the current body of published results.

However, recent nanoindentation experiments on olivine single crystals recorded ‘pop-in’ events in the raw mechanical data. These pop-in events occur close to the plastic yield point and represent an abrupt increase in displacement followed by a stress drop. We hypothesize that ‘pop-in’ events occur when there are relatively few dislocation sources available to nucleate new dislocations. Grain boundaries are a common dislocation source, and we suggest that, in previously published experiments, variability in the number of grain boundaries among samples leads to the discrepant results.

In this study, we test this hypothesis using nanoindentation in the region of pristine olivine grain boundaries. We use spherical indentation and place an array of indents straddling a grain boundary in a forsterite bicrystal and a natural olivine grain boundary of volcanic origin. This approach allows us to look for systematic changes in the pop-in behaviour as a function of distance from the grain boundary and test whether the grain boundary is a source of defects in olivine.

The results of this study will complement previous investigations of olivine by elucidating the role of grain boundaries in deformation of upper mantle rocks.

Strain and stress field evolution in the Andean orogenic front between 35-36ºS and its link with fluid migration

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The role of inherited structures in the development of the fold-and-thrust belt has been long recognised in the Southern Central Andes. Here we present our work focused in the deformation front of this part of the Andes (35-36ºS) to analyse the interaction between forelandward migration of the thrust front and previous normal structures but taking into account its role in the fluid migration depending on the stress-field variations.

In this area, the Malargüe fold-and-thrust-belt developed as a thick- and thin-skinned belt from the Late Cretaceous until present-day. The main phase of deformation started in the Miocene (~20 Ma) and the deformation front progressed eastward into the foreland in concomitance with the expansion of the magmatic arc in the same direction. The deformation in this belt involves previous rift structures of the Triassic-Cretaceous Neuquén Basin, one of the most important oil-producing basins in Argentina, that were reactivated under contraction as reverse and strike-slip faults, while new Andean faults both thick-skinned as thin-skinned were created. Many dykes and sills were intruded during the Late Miocene into the Mesozoic sedimentary sequence of the Neuquén Basin near the deformation front of this belt. These igneous bodies are potential reservoirs for hydrocarbons as it is shown in other parts of the basin.

Based on subsurface information (seismic data, oil-well logs, minifrac tests) as well as surface data (fault slip data, dyke and sill analysis) we hypothesise on how the stress-state changes and its influence in the faults that could act as flow paths for magmatic fluids as well for hydrocarbons. We identified three main orientations in the Mesozoic normal faults that bounded previous rift-related depocenters, a NNW set, a NNE set and a NW to WNW set. The first and second set (NNW and NNE) were inverted during Andean contraction probably due to their orientation, whilst the NW to WNW set does not appear to be inverted as reverse faults but with a strike-slip kinematic. This relies on the fact that these faults have the same mean orientation of strike-slip faults which affects quaternary deposits along with the mean orientation of dykes which present strike-slip faulting.

Using previous published data of our group as well as other's authors, we propose a model which relates the progression of the deformation to the foreland and the stress-state change according to the location in the fold-and-thrust belt. In this model during the first stage (17-10 Ma) the present-day front was on a foredeep position while the main deformation was located to the west and some of the normal faults started to be inverted. Subsequently the deformation progressed to the east and in the second stage (10-7 Ma) this area was under a compressive to strike-slip stress state. Under this regime, thin- and thick-skinned andean faults developed together with the reactivation of NW to WNW normal faults as strike-slip faults. These strike-slip structures were suitable for magma migration and many of the dykes and sills were emplaced following this trend. Finally, in the third stage (7-1 Ma), while the deformation continued its migration to the east, pre-andean NNW faults were inverted alongside with thin-skinned reverse and strike-slip faults that were developed under a compressive to strike-slip stress state which continues currently according to our fault-slip data and oil-well minifrac tests. Hydrocarbon migration gets favoured under this regime using the strike-slip faults as fluid conducts.

Unlocking the secrets of slow slip using next-generation seismic experiments and IODP drilling at the north Hikurangi margin, New Zealand

Rebecca Bell 1), Melissa Gray 1), Joanna Morgan 1), Stuart Henrys 2), Dan Barker 2), Phil Barnes 3), Laura Wallace 1), Demian Saffer 4), Katerina Petronotis 5) and the IODP Expedition 375 and Expedition 372 shipboard scientists

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Subduction plate boundary faults are capable of generating some of the largest earthquakes and tsunami on Earth, such as the 2011 Tōhoku, Japan and the 2004 Sumatra-Andaman earthquakes, together responsible for over 250,000 fatalities. However, in the last 15 years a new type of seismic phenomena has been discovered at subduction zones: slow slip events (SSEs). These are events in which slip occurs faster than the plate motion rate but too slowly to produce seismic waves. Slow slip events may have the potential to trigger highly destructive earthquakes and tsunami on faults nearby, but whether this is possible and why slow slip events occur at all are two of the most important questions in earthquake seismology today. Most well-studied SSEs (e.g. Cascadia and SW Japan) occur at depths exceeding 20 km; too deep for direct sampling and high-resolution seismic imaging. A notable exception to this lack of access is the north Hikurangi margin, New Zealand, where well-characterised SSEs occur every 1-2 years, over periods of 2-3 weeks at depths of <2 - 15 km below the seafloor. The large magnitude and close proximity of the SSEs to the seafloor makes it feasible to precisely locate, drill into, collect logs, sample, image and recover physical property information from 3D seismic and conduct near-surface monitoring of the area of the fault undergoing slow slip. For this reason the north Hikurangi margin has been the focus of a number of large international experiments in 2017-2018, the objectives of which and preliminary findings will be discussed in this presentation.

2D seismic reflection data collected in 2005 revealed thick high-amplitude reflectivity zones coinciding broadly with the source areas of SSEs at depths of 5 km below the seafloor. Without high-resolution velocity models of this zone and an understanding of the type of material that makes up the subducting plate the interpretation of these high-reflectivity zones is ambiguous. Constraining the origin of this reflectivity could give important clues as to the processes responsible for slow slip. In Dec 2017-Jan 2018 a 3D seismic experiment was conducted in New Zealand in an attempt to image the structure and recover the physical properties of the plate boundary in areas of slow slip. These experiments funded by NSF, NERC, Japan and New Zealand involved the deployment of 100 ocean bottom seismometers, 200 onshore seismometers and collection of 3D seismic reflection data. The instruments were deployed with high density to allow the collection of data suitable for the application of Full-Waveform Inversion to produce high-resolution velocity models.

In Nov-Dec 2017 and March-May 2018 two International Ocean Discovery Program (IODP) expeditions, 372 and 375, used scientific drilling in New Zealand for the first time to target slow slip events providing valuable calibration data for seismic models and revealing the lithology of material being subducted. In this talk I will discuss how these expeditions aim to reveal the geophysical environments of slow slip events and get closer to understanding what factors lead to slow slip. I will discuss preliminary findings regarding the lithostratigraphy and physical properties of the incoming sedimentary section from shipboard measurements and discuss potential implications for the source of high-amplitude reflectivity in the slow slip zone.

Rift superposition in the Turkana Depression and the birth of the East African Rift System

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Extensional deformation in the East African Rift Systen (EARS) is localised in two extensive regions of crustal uplift and volcanic construction, the Ethiopian and East African Domes. These high plateaux (average elevations of ~3,000 m and ~2,500 m respectively) are separated by the Turkana Depression (TD), a broad region of subdued topography (~500 m) in northern Kenya. Here, the EARS displays a wide zone of deformation (~300 km) over substantially thinned crust (~20 km), in stark contrast to the narrow rift morphology (~80 km) and thick crust (~35-40 km) of the surrounding domes. The topographic segmentation of the EARS into discrete plateaux led to the idea that these were the surface manifestations of upwelling mantle plumes. According to this model, Neogene-Recent active rifting began in the extended crust over the domes and propagated passively into the otherwise undisturbed basement of the TD. In contrast to this picture, the region is underlain by ~NW-SE trending Cretaceous-early Paleogene extensional structures associated with Anza and South Sudan rifting, marking an important period of earlier crustal modification. Moreover, the TD hosts the oldest manifestations of EARS-related volcanism (Eocene) and perhaps rift basin formation (late Paleogene?), as suggested by published seismic reflection data. However, despite its principal role in the chronology of EARS evolution, the morphotectonic evolution of the TD remains poorly understood.

Low-temperature thermochronology data (apatite fission track and (U-Th-Sm)/He, and zircon (U-Th)/He) from Precambrian basement and Late Cretaceous-Paleogene sedimentary rocks in the TD reveal a polyphase tectonothermal evolution of the upper Turkana crust spanning Cretaceous-Recent times. After an initial period of Early Cretaceous denudational cooling, thermal history modelling reveals that parts of Turkana began to subside during the Late Cretaceous-early Paleogene, in places accommodating substantial thicknesses of infill. This marked an important period of crustal thinning that may have facilitated the subsequent Eocene commencement of major volcanism in Turkana.

Beginning in the late Paleogene, basement rocks located in the footwall of newly formed, ~N-S trending normal faults experienced the onset of rapid cooling, marking the formation of a series of rift basins in Turkana and the earliest record of EARS-related extensional deformation in East Africa. The initiation of EARS rifting in the TD is likely due to the inherent weakness of its lithosphere, a result of earlier Cretaceous-early Paleogene crustal thinning. Thus, its hot, weak lithosphere was more adept to accommodate strain than the cold, thick crust beneath the surrounding domes. These findings illustrate the important role of lithospheric rheological heterogeneities in controlling the localisation and propagation of extensional deformation in continental rifts.

Exploring the role of salt tectonics in the South-Pyrenean fold-and-thrust belt

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In the foreland thrust belts of the Pyrenees, the Triassic Keuper evaporites have long been recognized as the principal detachment level for thrusting. The deformed Late Cretaceous to Eocene foreland basins of the Pyrenees show evidence of diapirism that has been often overlooked due to the more obvious imprint of thrusts and fault-related folds. We explore the variation of the salt-tectonics structural style along two classic transects of the Southern Pyrenees (Noguera Pallaresa and Noguera Ribagorzana rivers) addressing the role of halokinesis in the structural and sedimentary development of the basin. Appreciating the diapiric role of the Triassic source layer provides new explanations with strong implications for the kinematics of compressional deformation and the amount of orogenic shortening.

The areas described include precursor diapirs, that started developing during the Mesozoic pre-orogenic extensional episode of the Pyrenees, and areas where halokinetic movements were triggered during the Pyrenean compression. We report the case of the Sierras Marginales foothills, a polygonal system of salt ridges and intervening synclines, initially outside of the area affected by rifting and then filled with early synorogenic sediments that now appears intensely imbricated. The second case study is the Montsec thrust and Ager basin, a linear salt wall and adjacent syncline with a long history dating back to the extension, subsequently squeezed during the orogeny. Also discussed is the case of the Pobla de Segur and Senterada intramontane conglomerate basins on the Boixols and Nogueres thrust sheets, which shows a complex history of sediment and thrust sheet loading onto a wide diapir which through salt expulsion causes the tilting of the entire basin.

Our field observations lead to fundamental questions regarding the relative roles of buckling and drape folding by salt evacuation, the mechanisms that drove the early, salt-cored folding to late imbrication, and the causes favoring polygonal salt ridges and minibasins vs. linear salt walls (i.e. basement faulting vs relative evaporite/overburden thickness).

Comparison between two deep-water fold-and-thrust belts: Outer Tuscan Nappe (Northern Apennines, Italy) vs. Baram DWFTB (NW Borneo)

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Most of the fold-and-thrust belts develop in a deep-water environment (deep-water fold-and-thrust belts, DWFTBs), at both continental passive and active margins, mainly driven by gravity (near-field stresses) and/or tectonic forces (far-field stresses) respectively. Some margins entail a mixed-mode, where both the stresses act concurrently. This study represents a first attempt of applying to a fossil case-study, the Outer Tuscan Nappe (OTN) fold-and-thrust belt, the concepts and classifications recently proposed for modern DWFTBs, and compare it with a the northern part of the active Baram DWFTB (NBFT).

The OTN is an imbricate thrust system in the Northern Apennines of Italy, emplaced during the Early Miocene in the framework of the collision between the continental lithosphere of the Adria and the already formed Alpine orogen. It involves a 1.5 km thick, Oligocene-Early Miocene siliciclastic turbidite unit, overlying a 500 m thick succession of pelagic Eocene-Lower Oligocene marls and calcarenites that form a major basal décollement.

The NBFT is located off-shore Sabah (NW Borneo), developed following subduction of the Proto South China Sea and emplacement of the thinned passive margin of South China under the northern Borneo in Early Miocene. The rise of Borneo after collision shed sediments to the surrounded basins, subsequently accreted within the DWFTB offshore Sabah. The fold-and-thrust belt incorporates up to 1.5 km of late Early Miocene-early Middle Miocene deep marine shales, overlain by up to 4 km of Middle Miocene-recent clastic sediments. Both case-studies are detached above a shaly landward-dipping décollement, but they differ in geometries, kinematics and mechanics. The OTN is ~ 33 km long and the internal shortening (19 km, 38%) is accommodated by six main thrusts. The compressional domain in the NBFT varies from 70 to 81 km, and the shortening (6 to 14 km, 7 to 14%) is accommodated by five to six main thrusts. The amount of internal shortening along the OTN is higher than along the NBFT. The maximum shortening is achieved up-dip and decreases oceanward. The OTN was active between Late Aquitanian and Late Burdigalian at a rate of ~ 10 mm/yr. The NBFT was active since Early Middle Miocene but significant syn-kinematic deposits, late Early Pliocene in age, indicates that it shortened considerably since this time; at a rate of ~ 3 mm/yr.

The OTN high wedge-taper angle (8°) is in agreement with the values typically reached by far-field stress-driven DWFTBs. The NBFT average wedge-taper angle (3.5°) can be associated to a mixed-mode DWFTB, i.e. a far-field DWFTB affected by gravity-driven shortening due to high sedimentation rates.

Besides both case-studies are thin-skinned FTBs developed during an early collisional stage, detached above a landward-dipping shaly detachment, they are substantially different in terms of geometry, kinematics and mechanics. This is due to their different origins since the OTN was driven by crustal shortening while the NBFT is mainly driven by crustal-shortening with a gravitative component deriving from the presence of extensional tectonics in the inner part of the system.

Constraining the evolution of HT shear zones in the Himalayan mid crust: fusing structural geology and petrochronology

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The mid-crust of the Himalaya is represented by the Greater Himalayan Sequence (GHS), one of the major tectonic units of the Himalayan belt exposed for nearly ~ 2500 km. It has been considered as a coherent tectonic unit since long time, bounded by the South Tibetan Detachment to the top and the Main Central Thrust to the bottom. However, a multidisciplinary approach including structural analysis joined to petrology and petrochronology allowed to recognise several high-temperature shear zones in the core of the GHS along the belt, with top-to-the S/SW sense of shear (High Himalayan Discontinuity: HHD, Montomoli et al., 2013, 2015; Carosi et al., 2018). This tectonic feature running for several hundreds kilometres is documented in several sections of Western and Central-Eastern Nepal dividing the GHS in two different portions. We present also new results of a structural and geochronological transect in the GHS of Marshyangdi valley (Manaslu-Annapurna massifs, Central Nepal).
In situ U-Th-Pb analysis of monazite constrains the timing of top-to-the S/SW shearing between ~ 28 Ma and 17 Ma during the retrograde path of the hanging wall rocks in the sillimanite stability field.
In addition to this, the long lasting activity of the HHD under medium to high-grade metamorphic conditions controlled the P-T-t paths of the hanging wall and footwall rocks at the point that they recorded maximum P-T conditions at different times. Earlier exhumation of the hanging wall was triggered by the contractional kinematics of shear zone, whereas in the same time span the footwall underwent increasing P-T conditions.
The similarity in timing of movement of this shear zone and the later Main Central Thrust, from deeper to upper structural levels, fits with an in-sequence shearing tectonic model for the exhumation of the Himalayan mid crust.

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Multiple influences on measured fracture attributes in a frontal anticline: a case study from The Sawtooths, NW Montana

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Swift Anticline is a thrust-related frontal structure of the Sawtooth Range, NW Montana. Excellent exposure of fractured Mississippian Madison Group carbonates across this reservoir-scale structure make it a suitable outcrop analogue to fractured carbonate reservoirs in fold-thrust belts, particularly of the laterally-equivalent Western Canada Sedimentary Basin. The frontal anticlines of the Sawtooth Range have been important sites for field-based appraisal of fracture patterns, particularly with respect to the link between folding and fracturing. Several of these outcrops have provided field data for work on predicting fracture orientations in folded strata (e.g. Stearns, 1964). Observed fracture patterns at Swift, however, are complex and vary significantly in 3D. Further, they do not appear to conform to existing models of fracture orientations in contractional settings. In this study we adopt a combination of field-based and digital interpretation approaches: we supplement field measurements of fracture attributes with virtual outcrop derived data. This approach allows fracture attributes (orientation, intensity and length) to be extracted at a range of scales, through several structural, stratigraphic and along-strike positions.

Results show that measured fracture attributes at Swift Reservoir are primarily influenced by structural position: bedding-normal Mode I fractures are dominant in strongly deformed zones of high curvature while mode II fractures record increases in intensity and length-scale on gently dipping back-limb positions. Along-strike variation in fracture orientations records asymmetry along the anticline axis and highlights several fracture corridors which serve as lateral accommodation structures in the fold. Variation in fracture orientations through the stratigraphy are impacted both by mechanical properties of units, and by the presence of discrete mechanical boundaries along which strain was apparently localised during deformation. Finally, data derived from a range of scales (field-based; high-resolution virtual outcrop; satellite imagery) record significant variation in measured fracture attributes as measurement scale changes.

The combination of detailed digital mapping and fieldwork allows characterisation of fracture patterns at multiple scales, stratigraphic levels and structural positions. This approach highlights complex and variable fracture patterns at Swift Anticline which do not wholly conform to existing models of fracture development. Based on our data, we suggest that predicting fracture patterns in folded strata is not straightforward. The influence of multiple factors, including mechanical stratigraphy, structural position and scale-of-observation should be accounted for when attempting to make predictions of fracture patterns in the subsurface.

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The Campidano Graben (Italy): a Pleistocene re-activation of the Oligo-Miocene fault system of southern Sardinia

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In the current geological literature the Plio-Pleistocene tectonics of Sardinia has been often associated with the opening of the Southern Tyrrhenian Basin. However, this correlation is not based on solid data since the exact time in which the post-Miocene tectonics was active in Sardinia, the regional stress field and the kinematic behavior of the major faults have not been defined as yet.

We present the results of a detailed study based on seismic interpretation of the so-called Campidano Graben, the most important Pleistocene tectonic feature in Sardinia, which extends on-land from the Oristano Gulf to the Cagliari Gulf for more than 100 km in length and 15-20 km in width. Based on a revision and new interpretation of previous biostratigraphic data, the age of the fault activity of the Campidano Graben is Early Pleistocene and not middle-late Pliocene as attributed in the current literature. The area in which extensional tectonics was active during the Pleistocene roughly coincides with the southern part of the area in which the Sardinian crust was affected by the late Oligocene-early Miocene tectonics. This coincidence suggested us to investigate the relationships between fault systems active during the Oligo-Miocene and the systems active during the Pleistocene in order to find out differences and similarities.

The Pleistocene tectonic activity in the Campidano Graben is characterized by normal faults accompanied by a generalized uplift. The maximum thickness of the sedimentary sequence filling the basin exceed 1000 m. Most of the Pleistocene faults have remobilized faults active during the Oligo-Miocene tectonics.

The Campidano Graben is divided into two sub-basins separated by the Guspini-Sardara structural high. The northern sub-basin is bounded by N-S trending normal faults responsible for a W-E extension that did no exceed 2.03%; the southern sub-basin is limited by NNW-SSE oriented normal faults producing a WSW-ENE extension that reached 8.18%. Fault active during the Oligo-Miocene in the two areas have a similar pattern.

The Pleistocene tectonic evolution of Sardinia does not appear influenced by the coeval tectonics active in the Southern Tyrrhenian Basin. The extensional faulting and the associated generalized uplift recognized in Sardinia may have been caused, in our opinion, by an isostatic disequilibrium. Whatever the cause of the uplift and the consequent extension, the Pleistocene faulting appear to be a sort of collapse that produced the re-activation of Oligo-Miocene fault planes rather than the creation of new active faults.

The Himalayan metamorphic core along the Alaknanda-Dhauli Ganga valley (Garhwal Himalaya, India

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In the Alaknanda-Dhauli Ganga valleys (Garhwal Himalaya, NW India) a quite complete and well-exposed structural section of the Himalayan belt is present (Jain et al., 2014) starting from the Lesser Himalayan Sequences up to the Tethyan Himalayan Sequence.
In this contribution a detailed geological, meso- & micro-structural and petrographic reappraisal is presented, focusing on: (i) the distribution of index-minerals, (ii) the relationships between blastesis/deformation and (iii) the switch of main minerals recrystallization mechanism along the study transect.

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U-Th-Pb *in situ* monazite geochronology, from selected samples of key-structural positions (MCTZ up to STDS), allowed us to put an absolute temporal constraint both on the prograde metamorphic history and on the exhumation-related metamorphic overprint.
These data, joined with the ones from the geological literature (e.g. Thakur et al., 2015; Hunter et al., 2018) shed new insights on the tectono-metamorphic evolution of the Himalayan metamorphic core in this portion of the belt.

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Gravity-driven structures and deposits resulting from slope collapse in the margin of a carbonate platform (Pennsylvanian, Cantabrian Zone, NW Iberia)

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Lower- slope to basin-floor deposits associated to isolated microbial carbonate platforms of the Valdeteja Formation (Carboniferous foreland basin of the Variscan Orogen, NW Spain), including large slide blocks and debrites, display a combination of contractional and extensional structures which include thrusts, backthrusts, folds, extensional faults, joints and boudinaged beds. Once restored to their initial attitude, all structures indicate a transport direction towards the NNE-ENE. This azimuth coincides with the direction towards which the thrust nappes of the southern branch of the Cantabrian Zone were emplaced during the Variscan Orogeny.

However, several types of evidence indicate that deformation took place in poorly lithified conditions, such as thickened hinges, hydroplastic fractures and folding of microbial limestones. These observations cast doubt on the tectonic origin of the structures, as they may also indicate a gravity-driven origin related to the collapse of the carbonate-platform slope. The latter interpretation is favoured after detailed mapping and structural analysis of the deformation fabrics, and is supported by features such as the rootless character of thrusts, the parallelism between transport direction of structures and paleocurrent orientation, the concomitant development of contractional and extensional structures, the development of listric extensional faults involving the Valdeteja platform, the inferred depositional setting (lower slope to basin-floor) and the geological context of the Valdeteja carbonate platforms during the Variscan deformation.

Thus, the structures can be classified as slumps caused by the collapse of the Valdeteja carbonate-platform slope. The obtained transport direction suggests that the platform displayed a WNW-ESE-trending margin with a NE-dipping slope that faced deeper and more distal portions of the Cantabrian Zone foreland basin.

Kinematics of the early Alpine collision wedge recorded in the Internal zones of the western Alps

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The internal zones of the western Alps include continental margin units and oceanic units of various metamorphic grade. Most of the continental units are derived from the Briançonnais domain, a former marginal plateau which was connected to the Iberian microplate through the Corsica-Sardinia-Provence area. Remnants of the distal rifted margin ‘toe’ can also be found, traditionally described as the Prepiemont units, now preserved in tectonic slices between the Briançonnais and the oceanic nappes. The oceanic nappes contain the former accretionary prism, with blueschist units dominated by Jurassic-Cretaceous sediments, and deeper eclogitic units with a higher proportion of oceanic crust (ophiolites). An initial phase of continental subduction resulted from the approximately N-directed Adria-Iberia motion during the Eocene. A large amount of sedimentary cover (upper Paleozoic and Mesozoic) was detached, and maintained at relatively shallow crustal levels. Other areas, where detachment levels are less well developed due to late Hercynian or Mesozoic paleogeographic evolution, were buried more deeply beneath the accretionary prism.

This early continental subduction wedge has experienced strong overprinting as a result of collision with the European crust, developing a regional-scale arcuate shape (in map-view) during the Oligocene in the Western Alps. During this ‘2nd’ stage, the former subduction wedge was progressively ‘extruded’ westwards in response to continued indentation by the Adria upper mantle. This produced large-scale tilting and rapid exhumation in the core of the arc, with exposure of the deeper portions of the stacked complex.

The kinematics of the ‘1st’ stage are recorded in the central and southern parts of the western Alpine arc by small-scale structural deformation features, with N to NW-directed tectonic transport criteria which follow the trend of the arc, and thus pre-date its formation. This structural history is consistently observed from the shallowest units (the so-called Embrunais-Ubaye nappes, some of which are described as being emplaced gravitationally over the Paleogene flexural basin), to the deepest eclogitic basement units, through the Briançonnais, Prepiemont and oceanic Schistes Lustrés zones.

Large-scale (kilometric) N-directed fold-and-thrust structures such as ramp anticlines and hangingwall cut-off relationships are locally preserved, especially along the boundary between the continental and oceanic units. Some preliminary $^{39}Ar/^{40}Ar$ dating on phengites, associated with a synsedimentary mega-breccia (olistostrome) located in the footwall of the oceanic nappes, indicate that the most distal margin units belonging to Iberia have been subducted southwards beneath the accretionnary wedge during the early Eocene. This is consistent with recently published geodynamic models. The eastward ‘subduction’ of the European lithosphere, imaged using geophysics (Zhao et al., 2015), is recorded by the evolution of the Pennine Thrust and is younger (early Oligocene).

This proposed 2-stage orogenic history enlights a kinematic change which may be linked to an evolution from Adria-Iberia collision, involving a thinned lower plate (Briançonnais, Prepiemont), to incorporation of the European lithosphere itself.

The Influence of Base Salt Relief on the Structural Evolution of Salt and Overburden: Case Study from the Outer Kwanza Basin, offshore Angola

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Imperial College London

Salt-influenced passive margins are widespread and may contain large volumes of hydrocarbons. However, they can be structurally complex, with their kinematic development being poorly understood. Classic models of salt tectonics divide such margins into updip extensional, mid-slope translational, and downdip contractional kinematic domains. Furthermore the faults, folds, and salt walls associated with each kinematic domain are typically assumed to form perpendicular to the maximum principal stress, which in gravitationally driven systems means broadly perpendicular to base salt dip. In this study we use high-resolution 3D seismic reflection data from the Outer Kwanza Basin, offshore Angola to show these models cannot explain the diversity of salt structures developing on passive margins, especially those defined by considerable relief on the base-of-salt surface.

We show rollers and walls in the mid-slope transitional domain of the Outer Kwanza Basin show three dominant trends, each characterised by different structural styles: i) salt walls perpendicular to the overall base salt dip, ii) salt walls parallel to the base salt dip, and iii) salt walls oblique to the base salt dip. Overburden seismic-stratigraphic patterns record the origin and evolution of the salt structures, allowing us to reconstruct deformation patterns through time and space. We show that each set of walls has a unique history, with synchronous phases of extension and compression occurring in adjacent structures despite their close spatial relationship. Our analysis suggests that, in the Outer Kwanza Basin, the structural evolution of the salt and overburden is predominantly controlled by base salt relief.

Changes in the downdip volumetric flux and velocity of the salt as it thickens and thins over topographic features cause local compression or extension, in addition to local changes in the base salt dip that can alter the direction of salt flow. This interaction with base salt relief creates locally variable stress fields which deform the salt and its overburden, overprinting the broader, margin-scale salt tectonics typically associated with gravity gliding and spreading.

As a result, salt walls in the Outer Kwanza Basin form at a range of orientations and demonstrate a complex structural evolution, independent of their overall position on the margin. We suggest that the base salt relief exerts a dominant control on salt-related deformation in the Outer Kwanza Basin as the salt is relatively thin compared to the magnitude of the relief. The overburden is therefore less ‘cushioned’ from the effects of base salt relief as it is translated downdip than in areas with thick salt and low relief.

Deformation and fluid flow associated to the Subligurian nappe detachment: insights from the Cinque Terre area (Northern Apennines, Italy)

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Vrije Universiteit Amsterdam

The migration of fluids through accretionary complexes and its relation with deformation is still relatively poorly understood. The northern Apennines of Italy represents a suitable area for this type of investigations. This study aims to contribute to this topic by focussing on the coastal sector of the northern Apenninic belt, where a major, regional detachment zone developed at shallow crustal levels crops out. Specifically, the study area is located in the Cinque Terre area (La Spezia province) and comprises the uppermost part of the Coastal Macigno Formation, which represents the Late Oligocene foredeep (Tuscan nappe), and the lowermost part of the tectonically overlying Eocene Canetolo Formation (Subligurian nappe), tectonically stacked during the post-collisional Miocene phases. The presented data result from high-resolution structural-stratigraphic logs collected across the detachment, along with analysis of calcite vein sets in terms of distribution, microstructure, and stable isotopes.

The investigated veins nucleated during the initial compression phases and subsequently evolved during exhumation-related extension of this area of the Apennines. They show increasing density/frequency towards the detachment that separates the Tuscan and Subligurian nappes. Relatively high vein concentrations at intermediate structural-stratigraphic levels are found in mesoscale thrust stacks, duplexes and fold zones. Veins that are parallel to the bedding contacts usually result from multiple crack-and-seal events, while veins oblique to the bedding respond to only one or two precipitation events. Locally, both sets record fluid overpressure conditions, evidenced by host rock inclusions. Compression-related veins present shearing, folding, pressure solution, or fracturing, whereas the veins formed during extension remain undeformed. Oxygen and carbon isotopic signatures suggest no or little influence of deep metamorphic fluids, testifying that the parent fluids were mainly composed of seawater that equilibrated to a variable extent with the host rock. This equilibration depends on 1) the continuity of the veins and 2) the lithology of the host rock.

New structural and petrological data for the Susa Shear Zone (mid-Susa Valley, Western Alps): Constraints on a polyphasic shear zone between eclogite and blueschist units

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In the Western Alps, nappes of different paleographic origin are stacked in the orogenic wedge. Subduction- and exhumation-related units are juxtaposed and have recorded different metamorphic peaks at different stages of the orogenic evolution (e.g. Dal Piaz et al., 2003). This study focuses on the tectonic and metamorphic evolution of the mid-Susa Valley (Inner Western Alps) where the tectonic contact between the Eclogite belt and the Frontal wedge is well exposed (Malusà et al., 2011). The Eclogitic belt consists of a meta-ophiolite unit (Internal Piedmont Zone, IPZ) which was coupled early in the tectono-metamorphic evolution with a continental margin unit (Dora Maira Massif, DM), while the Frontal wedge corresponds to blueschist-facies meta-ophiolitic units (External Piedmont Zone, EPZ). The IPZ is a remnant of the Mesozoic Alpine Tethys, and consists of meta-ophiolites with a thin metasedimentary cover (Balestro et al., 2015, and reference therein), whereas the DM corresponds to a composite Paleozoic basement covered by a siliciclastic and carbonate successions. EPZ consists of minor meta-ophiolites and a thick oceanic metasedimentary cover (i.e., the Schistes Lustrès; Tricart and Schwartz, 2006, and reference therein). The Susa Shear zone is the tectonic contact between the Eclogitic belt and Frontal wedge and is a first order structure (Gasco et al., 2011) which underwent a polyphasic evolution with development of two mylonitic foliations (Sm1 & Sm2), related to an early HP event and a late LP event respectively. The SSZ also shows a composite kinematic evolution, characterized by top to East and top to West shear sense during the Sm1 and Sm2 development, respectively. The white mica grains that define the mylonitic foliation are chemically zoned and record a gap in pressure between the first and the second event. Sm1 is mostly marked by phengite (Si apfu=3.5 – 3.65), while Sm2 is characterized by muscovite (Si apfu= 3.2 – 3.45). The first mylonitic event, syn-to-post kinematic respect to regional foliation (S2), juxtaposed (early coupling) units recording two previous tectonic regional events, and developed at different times and under different geodynamic regimes in each unit. The coupled units were successively affected by further deformation during uplift. Finally, the SSZ was reactivated during a later extensional deformation phase (second mylonitic event) defined by discrete extensional crenulation clevage (ECC). This study focused on detailed geological mapping, which provided novel structural information on the SSZ. Furthermore, the combination of microstructural and petrological data with geochronological data will allow a new reconstruction of the complete kinematic and tectono-metamorphic evolution of the boundary between eclogite and blueschist units.

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The Himalayan metamorphic core along the Alaknanda-Dhauli Ganga valley (Garhwal Himalaya, India)

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'Fake mylonites': Melt organisation, strain partitioning, and rapid freezing in the lower crust

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Partial melts can form as a result of crustal thickening due to orogenesis. Even small melt fractions weaken the crust, so that partially molten volumes should accumulate significant amounts of strain. However, relatively little is known of how strain partitions in partial melts, how long the melts stay liquid, and how effective the melt expulsion processes from the partially molten crustal volumes really are.

Using examples from the Western Gneiss Region (WGR), Norway, we consider a case of co-existing migmatites and shear zones. Field, image analysis, and microanalytical methods allow (semi)quantification of melt volume, rock mineralogy and mineral chemistry, and microstructures. Integration of these analyses implies effective but spatially very constrained syn-melt strain partitioning and, importantly, subsequent very rapid 'freezing' of the melts, preserving both the shear zone and migmatite texture. Geochemical analyses imply that despite these shear zones being very distinct syn-melt deformation zones they do not appear to have acted as effective melt conduits.

We propose a mechanism that allows i) syn-melt strain localisation at an outcrop scale through stress-driven melt organisation, resulting in relative competence differences in a partially molten rock volume; and ii) formation of a mylonitic appearance at outcrop that is entirely or mostly syn-melt, without subsequent 'true' mylonitic shearing in the solid-state.

Syn-melt shear zones that have not acted as effective melt transport channels and/or that have not accumulated post-melt deformation despite having a "classical" mylonitic outward appearance may be more common than conventionally assumed.

Promontory collision and the early Paleozoic Wuyi-Yunkai orogeny in South China

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Continental margins, especially passive margins, commonly exhibit promontories and reentrants. Where this is the case, collision between two continents is expected to start at a promontory or between two promontories. This leads to some unique geological processes at the site of promontory collision, including potentially deep subduction and burial of the continental crust of the promontory on the lower plate. A similar situation is where a small continent on the lower plate collides with a major continent, as in the case of India colliding with Eurasia.

The ca. 460-420 Ma (late Ordovician-Silurian) early Paleozoic Wuyi-Yunkai/Kwangsian orogeny in South China, mostly affecting the West Cathaysia terrane, is characterized by high-temperature and high-pressure (up to >1.0 GPa) metamorphism and extensive magmatism. The magmatism is characterized by S-type granites that formed due to partial melting of the crust. Lack of coeval arcs and ophiolite in South China led to the suggestion that the orogeny was an intraplate one, post-dating and unrelated to Gondwana assembly. However, intraplate orogeny is generally believed to be a far-field response to plate convergence (most likely collision) elsewhere, but no adequate candidate for such a collision has been recognized. In addition, intraplate orogeny is difficult to explain the high-pressure metamorphism. We propose here that the orogeny is a result of promontory collision.

We suggest that West Cathaysia in South China was (part of) a promontory on the Yangtze-West Cathaysia continent. The promontory, situated on the lower plate, collided with Terrane PT of Lin et al. (2018, Geology, v. 46, p. 319-322) in late Cambrian-Ordovician, leading to loading of the lower plate and formation of a foreland basin on West Cathaysia. The collision and the resulting slower subduction rate turned off arc magmatism at the site of collision and potentially elsewhere as well. Subduction of the remaining oceanic lithosphere in the adjacent reentrant(s) led to continued convergence between the two plates and subduction and progressive burial of the West Cathaysia continental crust at the promontory. The buried West Cathaysia crust reached upper amphibolite-granulite facies metamorphic conditions with partial melting occurring in late Ordovician-Silurian, generating S-type granites. Since conductive heating of large slabs of cold crust buried by thrusting is a slow process and heating up to upper amphibolite and granulite conditions can take tens of millions of years, the model readily explains that peak metamorphism and partial melting took place tens of millions of years after onset of collision. In this model, the late Ordovician-Silurian (Wuyi-Yunkai/Kwangsian) orogeny was a continuation of the Cambrian-Ordovician (Kunngan/Yu'nan?) collisional orogeny that took place at the late stage of Gondwana assembly. The model explains the unique features of West Cathaysia in the context of Gondwana assembly. It offers a solution to the biggest puzzle concerning South China in the early Paleozoic, that is, a major tectono-thermal event in South China, with characters of a collisional orogeny, took place tens of millions of years after the Gondwana supercontinent had been assembled and collision appeared to have been over.

Use of garnet and plagioclase as proxies of the evolution of ductile shear zones

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Ductile shear zones are the location of intense interactions between chemical processes and mechanical processes. All the mineralogical and textural evidences of these processes, are however difficult to retrieve because of their partial recording and the very likely later overprinting during later events. The challenge for petrologists is to propose conceptual models of shear zone formation, that includes mechanical and chemical processes, based on the partial petrological record. To characterize active processes during the initiation of a shear zone, we have studied shear zones precursors, characterized by very limited finite deformation. Our approach consists of a detailed petrological analysis, based on the high-resolution X-ray mapping. The use of XMapTools software allows us to define different generations of metasomatic and metamorphic phases that are linked to metamrophic / metasomatic / deformation events. We are also able to estimate local bulk compositions to estimate P-T conditions of the strain by forward thermodynamic modeling. In this contribution, we focus our attention on plagioclase and garnet, which preserve, through their chemical zoning, a large part of the shear zone development history.

In the Neves area (Tauern window, Eastern Alps, Italy), a granodiorite of Variscan age, which is made of quartz, saussuritized plagioclase, biotite and minor K-feldspar, is affected by Tertiary Alpine deformation, under amphibolite facies conditions. This deformation is marked by the development of discrete brittle fractures and ductile shear zones, which have nucleated along inherited brittle structures, metasomatic haloes surrounding fractures and mafic or aplitic dykes.. In this study, we focus our attention on a garnet-bearing shear zone developed along an interface between the granodiorite and a quartz-albite metasomatic halo, developed along a former brittle structure. The shear zone is made of quartz, plagioclase, biotite, phengite, garnet and minor K-feldspar. In the shear zone, 4 generations of plagioclase and 2 generations of garnet have been defined and linked to different fluid infiltration / deformation stages. The saussuritized plagioclase (PlI) marks the alteration of the initial magmatic plagioclase. In the metasomatic halo, saussuritized plagioclase are breakdown into almost pure albite (PlII). The main ductile strain stage is characterized by the crystallization of euhedral garnet (GrtI) on former saussuritized plagioclase sites and a new plagioclase with an albite-rich core and oligoclase rim (PlIII). Garnet is characterized by a growth zoning with an enriched-Mn core and an enriched-Fe rim. Thermodynamic modeling, based on local bulk composition and garnet composition, allows estimating P-T conditions of the ductile strain at 520°C and 0.55 GPa. A second generation of garnet (GrtII), marked by an atoll morphology with a Mn-rich island core (new garnet) and Ca-rich rim (former resorbed garnet). This texture is interpreted as a late fluid flow event. Finally, a last brittle event induced the pulverization of metamorphic garnet and plagioclase, the crystallization of a pure albite (PlIV) with adularia and epidote in garnet cracks and the breakdown of biotite into chlorite. The temperature of this stage, that could be related to a seismic event, is estimated at ~230°C. Our results demonstrate that ductile deformation in the middle crust is linked and promoted by metasomatism that could create a sufficient viscosity contrast between the original host rock and the metasomatic halo to localize strain. The detailed petrological analysis of an apparently simple shear zone reveals the complexity of the active processes during the initiation of the shear zone, which cannot be considered only as the mechanical effect of the strain.

Structural variation across a submarine fold and thrust belt, South Falkland Basin

Dave McCarthy; Thomas Dodd
British Geological Survey

High quality seismic data from submarine fold and thrust belts provides a spectacular opportunity to study the evolution of these complex settings. The South Falkland Basin is no exception. Subduction beneath the South American plate along the Magallanes–Fagnano Fault becomes transpressional along the North Scotia Ridge, whereby the Burdwood Bank, has been accreted on to the southern margin of the Falkland Plateau. This resulted in the downwarping of the underlying Mesozoic shelf, with reactivation and development of normal faults that displace both the basement and Cenozoic sediments. This tectonic regime, thought to have initiated in the Miocene, and was accompanied by the development of a fold and thrust belt and foreland basin. This fold and thrust belt can be considered to be an offshore extension of the Magallanes fold and thrust belt of Terra Del Fuego and has a similar complex of north-vergent thrust geometries.

This contribution provides a detailed description of the fault architecture using a 2D and 3D seismic dataset. Key reflectors and faults were mapped to produce contour maps in depth of the main horizons. The foreland basin displays a range of fault structures of varying generations, suggesting reactivation of pre-existing fault structures, as well as development of new structures.

The FTB itself displays the characteristic range of structures from the deformation front to the hinterland. The frontal thrusts cut through post-Early Paleogene sediments and appear to have a decollement at approximately the Top Cretaceous unconformity, although thrusts in the hinterland appear to detach at a deeper level.

Furthermore, the style of thrusting varies from thin-skinned in the east to thick skinned in the west. The thin-skinned deformation is illustrated whereby undeformed Mesozoic reflectors are visible beneath thrust sheets, while thrusts in the western area are more complex and include basement and sedimentary packages. This variation is largely controlled by the increasing depth to basement from west to east.

Thinning mechanisms of the continental lithosphere: contribution from the Alpine Tethys rifted margins

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The progress of seismic imaging over recent years considerably improved our knowledge of the general architecture of present-day rifted margins. In spite of this, the understanding of mechanisms enabling the thinning of the continental lithosphere ultimately leading to breakup still represents a critical challenge. Such a situation is the consequence of the limited access to basement deformation in present-day margins and requiring the finding of onshore analogues. In that perspective, the Alps represent a key natural laboratory sampling from upper to lower crustal levels as well as the lithospheric mantle recording the extreme thinning of the continental lithosphere during the Jurassic rifting associated to the opening of the Alpine Tethys.

This contribution aims at exploring how the continental lithosphere thins: which structures can accommodate the deformation and eventually how far the initial architecture of the lithosphere may control subsequent rifting development. Subsequently, observations from the remnants of the Alpine Tethys are integrated into two-dimensional thermo-mechanical models of the lithospheric thinning addressing the importance of the initial pre-rift architecture.

Our results show that the initial Permian post-orogenic event significantly modified the continental lithosphere architecture by creating “inheritance” that has first-order importance on the following Jurassic rifting at all scales. Strongly influenced by this previous Permian event, Jurassic rift-related structures form from the complex interaction between large-offset normal faults associated with the development of anastomosing shear zones and decoupling horizons. We propose that these structures will accommodate the lateral extrusion of some crustal portions in the necking zone (e.g., mid-crustal levels). It results in the formation of a hyper-extended domain composed of the juxtaposition of various pre-rift levels with different pre- and syn-rift P-T histories (e.g., upper against lower crust but devoid of mid-crustal levels).

Altogether, these results highlight the critical role of the extraction of mechanically strong layers of the lithosphere during the extreme thinning of the continental lithosphere and allows us to propose a new model for the formation of continental passive margins.

Two opposite kinematics shear zones in the Alaknanda – Dhauli Ganga valleys (NW India): insight from microstructural and geochronological investigations

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Shear zones play a fundamental role in building up the architecture of the orogens and deeply affect their tectono-metamorphic evolution. Nevertheless, constraining the temporal evolution of a shear zone is a key problem to face with in the study of a collisional belt (Challandes et al. 2003). Since shear zones are characterized by intense deformation and are preferential path for fluid circulation leading to mineral reactions, the interpretation of geochronological data may be difficult. Therefore, a multidisciplinary approach based on detailed microstructural, chemical and geochronological investigations is necessary to deal with rocks coming from shear zones.

In the Himalaya, two opposite kinematics-crustal scale shear zones, the Main Central Thrust zone (MCTz) and the South Tibetan Detachment System (STDS), run for all over the length of the belt (Hodges 2000). Nowadays, in spite of numerous different studies focusing on the two regional shear zones, their age of motion is still debated. In the Alaknanda – Dhauli Ganga valleys (Garhwal, NW India) both the STDS and the MCTz crop out. We selected three representative samples from the STDS, located in the northernmost portion of the study area, in order to bracket its temporal activity. Microstructural observations reveal different deformation features from the uppermost sample to the lowermost one paired with decrease in $^{40}Ar/^{39}Ar$ ages on muscovite that is deformed in the uppermost sample and is undeformed in the lowermost one. $^{40}Ar/^{39}Ar$ dating on muscovite span from c. 16 Ma down to c. 14 Ma structurally downward.

The MCTz crops out in the southern part of the study area and is delimited by two discrete shear zones/faults, the Vaikrita Thrust at the top and the Munsiari Thrust at the base. Three samples from the Vaikrita Thrust, regarded as the MCT sensu stricto, were selected to constrain its time of shearing. Microstructural investigations reveal the occurrence of various generations of micas in three different structural domains: a relict, only locally preserved, foliation, a main mylonitic foliation, and a late generation of coronitic micas around garnet related to its breakdown. Biotite and muscovite separates from all three samples were dated by $^{40}Ar/^{39}Ar$ step-heating. Combining microstructural, chemical and geochronological data, we infer that the growth of mica along the main mylonitic foliation occurs at c. 9 Ma, whereas formation of coronitic muscovite yields c. 6 Ma. Therefore, our geochronological results support that the STDS and MCT in the Garhwal Himalaya are not coeval, and the movement along the MCT lasted until 7 Ma later than the STDS. This has important consequences on the current tectonic models used to explain the exhumation of the metamorphic core of the Himalaya, delimited by the MCTz and STDS.

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Geology and structure of the area around Paso de las Nubes, North-Patagonian Andes, Argentina

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The present study constitutes a lithological and structural analysis located in the central sector of the North-Patagonian Andes, between 41°06'00'' and 41°11'00''S, and 71°50'00'' and 71°33'40''W, east of the Tronador Mount. Currently there are two non-exclusive theories that explain the mechanism through which the North-Patagonian Andes at these latitudes were formed from Neogene times: the first of them proposes a compressive regime, while the second one considers a transpressive structural style.

The objectives of this study consisted in the mapping and analysis of the outcropping lithological units, the kinematic and chronological characterization of the observed structures, and the understanding of the deformation evolution and the structural style of the region.

The lithological characterization of the exposed units consisted in a petrographical analysis of all the units, a stratigraphic section and an Ar-Ar dating of the Tronador I unit. In order to develop the structural analysis, the methodology employed was constituted by: the identification of lineaments along with statistical and spatial analysis of the obtained data; the classification of the interpreted lineaments according to the unit they affected and their longitude; the measurement of fault slip data in 34 mesoscopic faults; the determination of the slip direction and the sense of fault-slip in each fault measuring the orientation of striae in fault planes and of associated secondary Riedel fractures.

The outcropping units mapped are: the Colohuincul Complex (Devonian-Permian), a Jurassic Volcano-Sedimentary Complex, the Miocene Coluco Formation and the volcanic Tronador Complex (Pleistocene), represented by the Tronador I and Tronador III units. An obtained age of 1.178 ± 0.057 My constitutes a high resolution dating for the Tronador I unit and helped refining the stratigraphy of the homonym complex, whose eruptive activity is limited between 1.2 – 0.3 My. The kinematic results from the structural analysis allowed to determine two fault systems: a transtensive population and a right-lateral strike-slip one.

Taking into account the obtained data and the regional tectonic context, the following inferences were made: i) the reactivation of former structures of the basement would have played a fundamental role in the Mesozoic-Cenozoic tectonic evolution of the region; ii) as the measurements reveal the presence of a strike-slip deformation component in the region, the mechanism of construction of the Andean orogeny at this latitude is more consistent with the transpressive regime, than to the purely compressive one; iii) a coupled structural evolution is proposed between the studied region and the Liquiñe-Ofqui Fault Zone in Chile.

Strain localization in quartz-rich rocks at the brittle-ductile transition

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The Calamita Schists (Elba Island, Italy) were affected by contemporaneous pluton emplacement and thrusting that caused the development of heterogeneous high grade mylonitic shear zones. During post-pluton emplacement cooling, brittle deformation localized in cataclastic bands that exploit mylonitic shear bands and cross cut the mylonitic foliation.

In order to gain insights on the deformation mechanisms and the processes controlling strain localization at the brittle-ductile transition, microstructural analysis, scanning electron microscope (SEM) observations and Electron Back Scatter Diffraction (EBSD) mapping of quartz have been carried out on quartz-rich mylonite and cataclasite samples collected on a shear zone within the Calamita Schists.

In the mylonite viscous deformation was accomodated by the recrystallization of quartz ribbons by dislocation creep (dominant prism <a> slip). During temperature decrease, strain hardening affected old, coarse, quartz grains, where sets of shear bands localized. Shear bands developed first by brittle cataclasis and hence were infiltrated by fluids that deposited new fine quartz and phyllosilicate grains. The interconnection of shear bands aimed by the coalescence of weak phyllosilicates produced a network of shear fractures that cross cut the mylonitic foliation.

In the cataclasite, the wall rocks recorded an earlier stage of dynamic grain size reduction of quartz by dislocation creep (prism <a> slip) which was hence overprinted in turn by granular flow and subsequent cataclastic deformation.

This study highlights that at the brittle-ductile transition quartzitic rocks are characterized by the interplay of ductile and brittle processes. Strain partitioning in ‘stiff’ quartz grains controls the nucleation of shear bands by brittle mechanisms. Shear bands act as fluid pathways enhancing softening by 1) dissolution-precipitation creep and 2) precipitation of weak phyllosilicates. Shear bands formed close to the brittle-ductile transition may hence act as mechanically weak and newly formed precursors over which subsequent brittle deformation can localize.

Pattern of deformation and vertical-axis rotation in strike-slip fault zone (Yunnan, China)

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A wealth of paleomagnetic data from Yunnan (China) showed in the past a predominant post-Cretaceous clockwise (CW) rotation pattern, mostly explained invoking huge (hundreds of km wide) blocks, laterally escaping (and/or rotating) due to India-Asia collision, separated by major strike-slip shear zones. Here we report on the paleomagnetism of the outcrops close to the Gaoligong dextral shear zone. Fifty paleomagnetic sites (503 samples) were sampled at variable distance (up to ca. 25 km) from mylonites exposed along the fault. Eighteen Jurassic-Cretaceous red bed sites yield systematic CW rotations with respect to Eurasia that peak at maximum (176 degrees) close to the fault, and progressively decrease moving eastward, up to be virtually annulled ca. 20 km E of mylonite contact. West of the fault, fifteen Pliocene-Holocene sites from the Tengchong volcanic field do not rotate. Thus, our data show that Gaoligong shear zone activity yielded significant CW rotations that were likely coeval to the main Oligo-Miocene episodes of dextral fault shear. The Gaoligong zone rotation pattern conforms to a quasi-continuous crust kinematic model, and shows blocks of <=1 km size close to the fault, that enlarge moving eastward. Rotation values and width of the rotated-deformed zone translate to a 230-290 km Gaoligong shear zone dextral offset. Our work shows that fault shear plays a significant role for Indochina CW rotation occurrence. However, significant fotations at distance > 30 km from main faults were also documented, so that additional tectonics-whose relative relevance has not been elucidated yet- must contribute as well to the rotation pattern. Our data, along with previous paleomagnetic and tectonic evidence, show that crust deformation of the Yunnan is extremely complex and still to be completely elucidated.

Microstructural significance of the mylonites from the Achankovil shear zone, South India

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Achankovil shear zone (AKSZ) of South India is a prominent crustal discontinuity in the region with a NW-SE trend and extends about 120 km through the states of Kerala and Tamilnadu, separates the granulite facies Madurai block to the north from the khondalite belt (Trivandrum block) to the south. Mylonite and mylonitic patches in sheared gneisses with numerous shear indicators have developed along the strike length of this shear zone. The general tectonic framework of the AKSZ indicates polyphase deformation and metamorphism, suggesting reactivation with domains on various scales exhibiting structures indicative of opposing shear senses. The sheared gneissic rocks exhibit a strongly developed penetrative foliation trending in the NW-SE direction with moderate dips towards SW. Detailed field and laboratory investigations reveal a complete sequence of relatively low strained and coarse grained protolith outside the shear zone to highly strained and fine grained ultramylonite in the centre of the shear zone. Three principal types of microstructures were recognized: preserved fabrics outside the shear zone (Type-1), partly recrystallised shear zone fabrics (Type-2) and reequilibrated shear zone fabrics (Type-3). A strong tectonic L-S fabric has developed characterised by grain size reduction, increasing flattening, elongation and dimensional preferred orientation of constituent minerals corresponding to a progression in strain. The microstructural studies of mylonites indicate that AKSZ has undergone extensive ductile shearing accompanied by fluid induced retrograde metamorphism. The progressive evolution of mylonite cause a change in the deformation mechanisms from dislocation creep through grain boundary sliding to grain size dependent diffusional flow, leads to strain softening. The present work is an attempt to understand the micro structural behaviour of the mylonites from the AKSZ and its tectonic significance,

Structural evolution of the Mizen Basin (Celtic Sea, Offshore Ireland) with special reference to basin inversion

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The Celtic Sea basins lie on the continental shelf between Ireland and north western France and consist of a series of ENE - WSW trending elongate basins that extend from St George's Channel Basin in the east to the Fastnet Basin in the west. The basins, which contain Triassic to Neogene stratigraphic sequences, evolved through a complex geological history that includes multiple Mesozoic rift stages and later Cenozoic inversion. The Mizen Basin represents the NW termination of the Celtic Sea basins and consists of two NE-SW trending half grabens developed as a result of the reactivation of both Caledonian and Variscan faults.

Previous studies in the Mizen Basin and surrounding areas have been based on 2-D seismic datasets. The present work sheds new light on the Mizen Basin structure and evolution based on 3-D seismic reflection data combined with wireline log and biostratigraphic data. The aims of this work are to i) study the tectonostratigraphic evolution of the Mizen Basin, ii) study the style and timing of the inversion structures and iii) highlight the role of non-coaxial extension and shortening on fault reactivation and segmentation. 3-D seismic coverage and a syn-tectonic stratigraphic sequence that is much better preserved than in the basins to the east makes this area an excellent location to study and understand the style and timing of inversion of the Celtic Sea basins.

Seismic interpretation within the study area has revealed three main faults populations consisting of a set of NE-SW-striking basin bounding faults, set of E-W-striking minor normal faults and a set of NW-SE-striking dextral strike-slip faults. Sediment thickness distribution and fault analysis indicates that the basin bounding faults were active as normal faults from Early Triassic to Late Cretaceous. Most of the fault displacement took place during Berriasian to Hauterivian (Early Cretaceous) times, with a NW- SE direction of extension. A later phase of Aptian to Cenomanian (Early to Late Cretaceous) N-S oriented extension gave rise to E-W-striking minor normal faults and reactivation of the pre-existing basin bounding faults that propagated upwards as arrays of segmented normal faults.

As for most of the Celtic Sea basins, the Mizen Basin experienced a period of major erosion during the Palaeocene attributed to tectonic uplift. Cenozoic Alpine inversion affected the study area from Middle Eocene to Miocene times causing reverse reactivation of the basin bounding faults and the formation of NW-SE-striking dextral strike-slip faulting. The different styles of deformation observed during extension and inversion are, to a large extent, controlled by the orientation of Variscan structures that localised strains throughout the evolution of these basins.

Role of salt detachment in the fold belt of the axial zone of the Eastern Cordillera, Northern Andes

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The external part of the northern Andes of Colombia is characterized by the Eastern Cordillera (EC). This mountain belt is a double verging thrust system formed during the Cenozoic by the inversion of a Mesozoic back-arc rift. The tectonic configuration of the EC has been described in several studies that reflect the diverse conceptions. The foothills of the EC are dominated by foreland-directed thrusts, extensively documented in abundant literature because of its hydrocarbon productivity. In contrast, the axial zone (Sabana de Bogotá) consists of a fold belt without a dominant vergence nor major thrust translations, which has been much less documented. In this work we have constructed a series of structural sections with sequential restorations based on 2D seismic lines and a revised mapping obtained from own field work and a compilation of other authors structural surface data.

The structural style defined for the Sabana de Bogotá fold belt suggests detachment over a weak décollement level. We have been incorporated salt tectonics concepts (e.g. Hudec and Jackson, 2001) to develop a detailed geological model of this axial part of the EC. Even though the salt presence in this region has been reported by numerous authors (including numerous salt springs and occasional diapir occurrences at the surface), to date there was no detailed structural model that addressed the origin of the main structures and their possible relationship with salt as detachment level or potential diapiric phenomena. We address the structure of the Sabana in the light of this new perspective and a new chronology of the compressional deformation which allows to re-evaluate the petroleum system in this zone of the EC, as well as to provide an analog for other areas in Colombia where salt has played an important role in the tectonic-sedimentary evolution and has been overlooked.

Shear deformation in the Southern European Variscan Belt: kinematic of the flow and geochronological constraints

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Recent models for the Southern European Variscan Belt propose the existence of a large right-lateral strike-slip fault known in the literature as East Variscan Shear Zone (EVSZ, Matte 2001; Corsini and Rolland 2009). This sector of the Belt was fragmented and reworked during the subsequent Alpine Orogenesis and because of this the correlation between the Variscan fragment in the Mediterranean area are difficult and the occurrence and the extent of the EVSZ is currently still debated.

We focused on shear deformation in a fragment of the Variscan Belt unaffected by further Alpine deformation (Maures-Tanneron Massif, southern France) and portions poorly reworked by Alpine Orogeny (Alpine External Crystalline Massifs, Western Alps).

Our structural, microstructural, petrographic and kinematic analyses coupled with in-situ U-Th-Pb geochronology on syn-kinematic monazites, revealed that all of these sectors are affected by Variscan shear zones (Ferriere-Mollières shear zone in the Argentera Massif; Emosson Lake-Val Bèrard mylonitic zone in the Aiguilles Rouges Massif; Cavalaire Fault in the Maures Massif) that formed during a pure-shear dominated transpression. The studied shear zones show a similar structural and metamorphic evolution with the well-known transpressive Posada-Asinara shear zone in northern Sardinia (Carosi and Palmeri 2002; Carosi et al. 2012).

If we restore the counterclockwise Oligo-Miocenic rotation of the Corsica-Sardinia block and of the Western Alps, all the studied sectors lie in lateral continuity. Our structural and geochronological data are therefore in agreement with the presence of a large long-lasting right-lateral strike-slip shear zone in the southern sector of the Variscan Belt. The EVSZ should be intended as a network of minor shear zones which forms progressively with the progress of the deformation.

Further studies are needed in order to better understand the orogen-scale process that lead to the formation of the EVSZ and to check if this structure can be related with others large-scale strike-slip shear zones active during Variscan time and with similar metamorphic condition (i. e. strike-slip shear zones in the Iberian Massif and in the Armorican Massif).

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Photogeology in the 21st century - 3D structural analysis from digital photographs

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Photogeology is an established technique that has been used to interpret geology and geomorphological features by examining aerial photograph stereo-pairs using a stereoscope. Since the advent of modern digital cameras, the increase of computational power (CPU and GPU speeds) and sophisticated computer vision algorithms in the 1990s, this traditional method has seen a transformation. Nowadays, a workflow known as Structure-from-Motion Multiview Stereo (SfM MVS), commonly referred to as digital photogrammetry, allows to build ultra-high (sub-mm) resolution 3D textured models and coloured point clouds (comparable to those from laser scanners/LIDAR) from a series of digital photographs. If a best practice data acquisition and image processing workflow is employed, high fidelity and geometrically accurate 3D models of geological outcrops and hand specimens can be built.
The nuts-and-bolts as well as limitations of SfM MVS are discussed and the tools that allow the extraction of structural data from coloured point clouds and raster images such as orthomosaics are described. A range of examples covering multiple scales are presented including 3D datasets computed from aerial imagery acquired by Unmanned Aerial Vehicle (UAV), as well as rock outcrops captured by a handheld mirrorless camera. Comparisons to traditional field measurements show that digitally collected orientation data from 3D photogrammetric models are not just reliable but also more comprehensive and therefore perfectly suited for detailed structural analysis and assessment. The relatively simple and low-cost SfM workflow will ultimately allow us to draw/build better geological maps/models with higher fidelity in a fraction of time compared to traditional geological mapping methods. Hence it should be considered an essential tool, such as the old and trusty rock hammer, by any (structural) geologist in the 21st century.

High-angular resolution electron backscatter diffraction analysis of lattice distortion in geological materials

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Microstructural analysis of deformed rocks is central to interpretation and modelling of deformation mechanisms, rheological properties, and associated geodynamic phenomena. Intragranular lattice distortions are a key part of this microstructural record and are most commonly analysed using electron backscatter diffraction (EBSD). Unfortunately, conventional analysis of EBSD patterns, employing Hough-transform-based indexing of each pattern, only reveals a fraction of the recorded information. Conventional EBSD only measures misorientations greater than a few tenths of a degree and cannot measure elastic strain. More information can be revealed using high-angular resolution electron backscatter diffraction (HR-EBSD), during which image processing of the diffraction patterns is used to probe very subtle variations in orientation and strain. The HR-EBSD method has precision in misorientation angles on the order of 0.01 degrees and, critically, can also measure elastic strain with precision on the order of 0.0001. The precise misorientation angles are accompanied by improved determination of misorientation axes, relative to conventional EBSD, allowing reasonable estimates of densities of geometrically necessary dislocations. Similarly, the elastic strains can be used to calculate residual stress variations currently stored in the rock. These capabilities open a wealth of new opportunities for investigating wide-ranging deformation processes. Results from naturally and experimentally deformed rocks reveal complex distributions of multiple dislocation types and stresses that vary by hundreds of megapascals over length scales of a few micrometres. These observations provide the basis for a new generation of models of deformation mechanisms and rheological properties.

POSTERS

The importance of stratigraphy and sedimentary structures in fault and fracture development in fluvio-deltaic sequences

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It is well known the thickness and mechanical strength of sedimentary beds can exert a strong control on fracture and fault properties, however, little work has been done on the impact of sedimentary structures and stratigraphic architecture. We aim to fill this gap through investigating, through detailed fieldwork, statistical correlations between stratigraphic/sedimentary features and fracture/fault attributes.

The field site is a continuous succession of Westphalian C Coal Measures between St. Mary's Lighthouse and Hartley Bay (Northumberland Basin). Situated roughly 4 km north of the Ninety Fathoms fault, which forms the southern margin of the Northumberland Trough, the area is cut by numerous centimetre to decimetre, strike-slip (E-W, NW-SE & N-S) and dip-slip (E-W and NW-SE) faults, with associated damage zones. The stratigraphy is a typical fluvial-deltaic sequence comprising cycles of Sandstones, Siltstones, Shales, and Coals (e.g. The Low main and 6" seams).

During explorative fieldwork (2017) geological mapping (1:2,000 scale), sedimentary logging, mechanical stratigraphy (1) and the development of a fracture facies scheme has been undertaken. Through this work it was observed fracture termination and connectivity was often controlled by sedimentary structures (e.g. cross bedding, scour surfaces, mud draped ripples, load and flame structures). Detailed field maps of faults, fractures and sedimentary features at key locations in each bed are used to correlate between fault/fracture attributes (e.g. offset, slip vector, dip direction, termination type) and sedimentary or stratigraphic features (e.g. grain size variation, paleo-current direction, ripple type and bed thickness).

Mud draped ripples, point bars and large changes of grain size at bed boundaries strongly impact fault and fracture attributes. Mud draped ripples, especially when organic rich (and coalified), regularly cause fractures to terminate. Where mud-drapes don't exist ripples often deflect fractures but rarely cause them to terminate. Point bars cause complex fracture networks to develop and through going fractures become deflected by channel boundaries in cross section. Lens development within the fault core is considerably more likely when thin sandstone units with medium to coarse grain size is surrounded by fine grained material.

This work suggests that it may be possible to predict fault and fracture properties from sedimentology if the regional tectonic setting is known. This would prove particularly powerful as an input for fluid flow simulations, such as dynamic simulations of hydrocarbon flow in reservoir modelling, which use sedimentary architectures, geometries and stacking patterns derived from outcrops.

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Deformation pattern in the thrust-related Parmelan Anticline (Bornes Massif, Subalpine Chains, Haute-Savoie, France): preliminary results

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The Parmelan Anticline is located in the frontal part of the Bornes Massif where Upper Jurassic to Cretaceous sediments of the European passive margin overlain by Tertiary foredeep turbidites are exposed. The NE-SW trending Parmelan anticline is a box fold characterized by steeply dipping limbs separated by a wide flat-lying crestal plateau. The limbs and the crest represent discrete structural domains separated by narrow kinked hinge zones localized on inherited pre-folding NE-SW trending extensional fault zones. In this contribution, we present a preliminary reconstruction of the kinematic evolution of this anticline by combining structural data obtained from detailed field mapping with microstructural, petrographic and geochemical (stable carbon and oxygen isotopes) analyses. The relative chronology between different calcite vein sets, bed-parallel and tectonic stylolites and conjugate systems of reverse and strike-slip faults is described. Their relative timing with respect to folding (i.e. pre- syn- or post-folding) is determined by comparing structural data collected in different structural domains after bedding dip removal. Upon unfolding, our data illustrate that pre-folding deformation structures related to layer-parallel shortening or even older, such as different sets of veins and tectonic stylolites, and conjugate systems of subsidiary reverse faults, are widespread. Because of their pre-folding origin, these structural elements are almost homogeneously distributed irrespectively of their position within the anticline. Accordingly, our results confirm the fundamental role played by structural inheritance, either related or unrelated to the stress field active during folding, to drive fold evolution and the associated deformation pattern. In addition, petrographic and geochemical data both from pre-folding veins and from late-tectonic (strike-slip-related) veins provide insight into the circulation of fluids during deformation. These data on different sets of veins formed at different times during fold evolution, highlight the importance of late-stage deformation structures (such as conjugate systems of strike-slip faults with offsets limited to a few meters) to control the vertical conductivity of the fracture network. Our results bear important implications for fracture patterns and related fluid flow in folded carbonate platform reservoirs in fold-and-thrust belt.

The pegmatite paradox: competing rates of deformation and crystallization

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Fully crystallized granites, rich in feldspar, serve to strengthen the continental crust, while melts from which they crystallize are generally assumed to weaken the deforming crust and assist strain localisation into shear zones. However, outcrop evidence from many syn-tectonic granitic pegmatites within shear zones reveal little internal deformation, implying they crystallized in the absence of tectonic shearing; yet the pegmatites have outwardly shapes indicative of them having experienced significant deformation with a greater competence than the shear zone in which they are embedded. This is a paradox that challenges the general assumption that magma localizes deformation.

By describing and interpreting field relationships in a typical pegmatite/shear zone association (Torrisdale, NW Scotland), we suggest a mechanism by which syn-tectonic granitic melts may, in effect, act as competent bodies while still crystallizing. Crystallization can be pulsed as the concentrations of crystallization-inhibitors (fluxes) increase in residual fluids. Competence increase is enhanced by preferential crystallization on intrusion margins that serves to encapsulate residual melt inside stiff rinds. These in turn can form competent inclusions with residual melt expelled as wings during continued deformation. Modern estimates for the rates of feldspar crystallisation (cms.a^{-1}) from undercooled hydrous silicic magma to form pegmatites greatly outpace natural deformation rate estimates for shear zones. Thus, fully liquid granitic melts may only be present fleetingly; consequently, in these systems the presence of melts is irrelevant to the accumulation of tectonic strains.

On the tectonic structures of the Eaux-Chaudes massif (western Pyrenees): a Helvetic nappe type in the Pyrenees?

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The Eaux-Chaudes massif is a complex south verging fold-and-thrust structure located in the western Axial Zone of the Pyrenees. The stratigraphic succession consist of Upper Cretaceous limestones lying unconformably directly on the Paleozoic basement. The structure has been interpreted as a duplex in Cretaceous rocks with a roof thrust carrying allochtonous Paleozoic rocks, called the Eaux-Chaudes thrust (Ternet, 1965).

Our initial work consisted on field analysis and mapping, structural data collection and sample collection followed by cross-section construction. Thin section analysis allowed us to quantify microstructural features and to estimate paleotemperatures by Raman Spectroscopy of Carbonaceous Material (RSCM).

Our preliminar results provide new elements to reassess the former interpretation: overturned bedding polarity and high-strain shearing have been identified within an allochtonous Upper Cretaceous unit, which overall forms a large basement-involved recumbent anticline with Paleozoic rocks in the core, much in the style of the Helvetic nappes of the Alps. Kinematic indicators as stretching lineation, angular relationships between schistosity and bedding, and S-C type structures evidence a south directed tectonic transport for the structure. As strain intensity increases in the overturned fold limb, recrystallization and shape-preferred orientation of calcite grains appears. The recrystallized matrix grain size ranges between 10 and 35 µm. Five samples have been analysed by RSCM and fitted them by Beyssac method (Beyssac, et al. 2002), which yielded paleotemperatures above 320ºC (i.e. near lower greenschist facies) in upper Cretaceous rocks.

These results lead us to propose a new interpretation of the Pyrenean deformation conditions in the northern Axial Zone of the Pyrenees, characterized by high ductility with a subordinate role of thrust faulting.

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eRock: on online, open-access repository of virtual outcrops in 3D

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The strong potential of virtual outcrops to provide detailed geological information means they are increasingly used by the geoscience community as a research tool. 3D reconstructions are also gaining traction as an effective means of communicating geological complexity within industry and academia, and are increasingly used as sub-surface analogues from which quantitative data can be extracted (e.g. Rittersbacher et al., 2014; Cawood et al., 2017).In spite of the visual appeal of virtual outcrops they are currently underexploited as a teaching resource and as a means of engaging the public with Earth Science. We attribute this to a lack of digital resources that present web-viewable virtual outcrops in an accessible and organised manner. A number of projects in other disciplines are currently using web-based 3D viewers as open-source archival/educational tools, but such resources have not yet been systematically developed in the geoscience community.

Here we present eRock, an online repository of web-based 3D virtual outcrops and hand-specimens. This project aims to provide the geoscientific community, educators and the general public with a multitiered, accessible resource, suitable for users with a range of backgrounds and objectives. eRock includes virtual outcrops and samples from localities around the world, together with key information and metadata for each 3D geological model. The majority of hosted virtual outcrops are fully available: users may download reconstructions and perform analysis on datasets from the repository. We provide a detailed workflow for researchers to download virtual outcrops from eRock, georeference downloaded data and perform geological analysis. Further, we provide the ability for collaborators to upload their own virtual outcrops, and share their results with the Earth Science community. For the public our aim is to share the variety and richness of geology, as well as provide a mechanism and resource for geological education that goes beyond the visual beauty of the outcrop or specimen. We anticipate that this project will provide an important link between the academic user of 3D reconstructions and the public, and an effective tool for engagement with, and training of, future geoscientists.

www.e-rock.co.uk

@eRocktweets

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Outcropedia, a public database of all important and beautiful outcrops in the World

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Outcropedia is an online public database sponsored by TecTask, the Commission on Tectonics and Structural Geology of the International Union of Geological Sciences (IUGS). The project was initiated by three structural geologists, Prof. Dr. C.W. Passchier, Prof. M. Jessell, and H. Lebit. The website was initially launched in 2010 under the outcropedia.org domain, but is currently being updated and remodelled under a new domain, outcropedia.be.webmapp.it. The website is organised so that users can upload their outcrop pictures with a short description and side information. Pictures and information of several locations can be added to build a geological route. All data is displayed in a global map, and can be searched by location or with the use of keywords incorporated in the description. In this manner, readers can observe pictures of the outcrops, get information on their location, their geological context, and where suitable, a list of related paper references.

The database has a double objective: (i) to make as many as possible first-class outcrops accessible to every geoscientist around the world, and (ii) to increase public awareness of the need of protection of threatened geological heritage around the world. The purpose is to make magnificent outcrops accessible to all interested parties, such as geoscientists, teachers, and the general public, so that they are provided with a powerful tool that can serve research, conservation, teaching, or even tourism purposes.

For researchers, it provides an unmatched contrasting and comparative tool, so that they can visit outcrops without the need of being physically there, though with the limitations inherent to photographs and uploaded graphic materials. This accessibility to outcrops facilitates the testing of published hypothesis by other researchers, thus contributing to making our science more objective. Through the outcrop exposure achieved with Outcropedia, it is intended that the geological heritage, arguably the least familiar for the population, will be increasingly protected from human activity. For teachers, Outcropedia provides a unique tool to obtain contextualised pictures of different and impressive geological features that can be used in lectures to increase the range of examples seen by their students, which will have a positive impact in their ability to recognize them elsewhere. For the general public, it provides a direct contact with the geological community, and a database where they will be able to find potential locations to be visited during their leisure time.

We have entered an era in which the amount of field-based research is decreasing, while its relevance still stands as great as ever, as it provides the base for all modelling and experimental research. From Outcropedia we would like to encourage all geoscientists to participate in the project, so that the ever growing geological knowledge can be graphically shared, and contribute to the protection of the geological wonders of our planet.

Late Variscan ore deposits in the Baccu Locci shear zone (SE Sardinia): a field example of structurally controlled mineralizations

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The Paleozoic basement of Sardinia hosts metal mineralizations (Pb, Zn, As, Ag, Au) that were mined until the first half of the last century. In the past, these mineralizations were often interpreted as strata-bounds orebodies and the implication of structural control in their origin were misinterpreted or not taken into account.
Detailed field mapping and structural analysis in the Baccu Locci mine area allowed to unravel how different paragenesis of mineralization are superimposed each other and their relationships with the Variscan structures.

The Baccu Locci mine district is located in a sector of the southern Variscan belt Nappe zone, where three tectonic units are stacked with a top-to-the-south transport direction and metamorphosed in lower-greenschist facies conditions. The Variscan tectonic evolution of the Baccu Locci area is characterized by an early shortening event testified by recumbent isoclinal fold, with well developed axial plane foliation, and overthrusting producing thick mylonitic shear zones, among which the Baccu Locci shear zone; a late shortening event led to the development of large upright folds; a post-collisional phase enhanced the antiformal structure by low-angle normal shear zones where asymmetric overturned folds developed; a latest event gave rise a set of NW-SE striking dextral reverse faults.

The orebodies in the study area are mainly Zn-Pb-Cu mixed sulfide lenses in the Baccu Locci shear zone and Qtz-As-Pb sulfide veins widespread in the whole mine district and surrounding areas. The mixed sulfide lenses are parallel to the mylonitic foliation, hosted in the hinges of minor order upright antiforms, that acted as traps for hydrothermal fluids bearing mixed sulfides. The Qtz-As-Pb sulfide veins crosscut the mixed sulfide lenses and are hosted in dilatational jogs developed in the hangingwall of dextral reverse faults related to the latest Variscan tectonic event. The releasing zones occur because the fault planes bend, becoming sub-horizontal where they crosscut the overturned limb of the asymmetric folds developed during the post-collisional phase.

The faults bearing the Qtz-As-Pb sulfide veins constitute a continuous mineralized field across the tectonic units separated by the Baccu Locci shear zone. This reflects a km-scale fault system affecting the whole nappe stack. The kinematic analysis of fault-slip data and S-C structures indicate roughly horizontal shortening and extension axes oriented N-S and E-W respectively, suggesting a paleostress field that gave rise to strike-slip tectonics during the final stage of the Variscan orogenic cycle.

Lithostratigraphic, structural and petrographic features of the Monte Banchetta – Punta Rognosa area (Western Alps, Italy)

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The Monte Banchetta – Punta Rognosa area identifies a mountain massif located between Troncea and Chisonetto valleys (Italian Western Alps). It consists of discontinuous oceanic and continental rocks, characterized by highly complex structural relationships and recently thought to form a mélange bounded by different oceanic units (Polino et al., in press and references therein). Based on original field and petrographic studies, the scope of this work is to give new and detailed data about lithostratigraphic features and tectono-sedimentary evolution of the rocks of this massif. Present work highlights the occurrence of three different successions recording during the Mesozoic the tectono-depositional evolution of continental, marine proximal and distal oceanic sectors. The continental crust succession consists of a composite pre-Triassic (?) basement, overlaid by a shallow depth marine sequence consisting of quartzite followed by meta-dolostone and dolomitic meta-breccia, characterized by polydolomitic clasts. This succession ends with calcschist, tentatively attributed to the lower Jurassic. The proximal succession, whose basement is unknown, is characterized by a heteropic sequence of polymictic meta-breccia (with dolostone and quartzite clasts), carbonate-bearing quartzite and quartzite containing dolostone clasts, wrapped by black shale; this sequence is overlaid by calcschist containing levels of green and black shale. The distal oceanic succession is composed of serpentinite with ophicarbonate, overlaid by heterogeneous supra-ophiolitic meta-breccia with both oceanic and continental-derived clasts, followed upsection by discontinuous levels of impure quarzite, locally containing thin layers of para-metabasite and plurimetric dolomitic olistoliths; this sequence is overlaid by calcschist, with scarce bodies of various meta-ophiolite. These rocks generally show an Alpine evolution characterized by HP-LT metamorphism, followed by LP-LT green-schists facies retrocession. The HP metamorphic peak ranges from omphacite-bearing to lawsonite-bearing blue-schists facies. Four folding phases have been recognized: both the first (D1) and the second (D2) deformation phases develop axial plane pervasive schistosity and are characterized, from meso- to large-scale, by non-cylindrical folds, which generally show NE-SW trending axes. The third phase (D3) is responsible for a small-scale crenulation cleavage and large-scale folding with generally ENE-WSW trending sub-horizontal axes. the fourth phase (D4) consists of gentle folding with N-S trending axes. In the studied area polyphasic shear zones also occur generally linked to D1 and D2 deformation phases, though often they show a late extensive reactivation. These folding and shear structures are cut by three brittle fracture systems, trending N60, N350 and N200 respectively, showing normal to transtensive movements. The features of the three identified and mapped successions in the Monte Banchetta – Punta Rognosa area give new constrains on the transition between the European distal margin and the Piedmont-Ligurian Ocean in this sector of the Western Alps.

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Geometry, Deformation Mechanisms and Seismic Style of Oceanic Transform Faults

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Oceanic transform faults vary internally in their ability to generate earthquakes along strike and down dip. Controls on this complex behaviour remain largely enigmatic. Thermal models are commonly used to explain a down-dip transition from seismic to aseismic deformation, however, for oceanic transforms, such models struggle to explain the full spatial distribution in seismicity.

The Troodos ophiolite, a fragment of Cretaceous oceanic lithosphere exposed on land in Cyprus, contains the Southern Troodos Transform Fault Zone (STTFZ). In this >5 km wide fossil fault zone, serpentinised mantle and mafic crustal rocks record the 3D structure and composition of an oceanic transform. Preliminary fieldwork from the STTFZ reveals mixed deformation styles at various stratigraphic depths. Brecciation and cataclasis dominate in crustal sections, whereas serpentinite shear zones display mixed continuous-discontinuous deformation in mantle rocks. Variable deformation intensities are documented in crustal fault zones, where cataclasites along dyke margins and pervasive breccias represent localised and distributed end-member deformation styles, respectively. Sulphide mineralisation is observed in many fault zones. Serpentinisation of mantle peridotite is pervasive and, away from shear zones, a mesh texture of serpentine-filled veins is noted. Serpentinite shear zones up to ~500m thick display anastomosing scaly fabrics, which transition to a closely spaced planar foliation, and discrete fault planes are common.

Viscous deformation is expected to dominate over brittle deformation with increasing depth and temperature, hence the attempt to explain transform seismicity with thermal models. Our STTFZ observations show temperature is not the only control. Brecciation of sheeted dykes is related to brittle deformation at shallow crustal levels whilst serpentinite shear zones mixed continuous-discontinuous deformation may be explained by the conditionally stable nature of serpentine. We hypothesise that to explain STTFZ observations, local and transient variations in temperature, fluid pressure and strain rate can allow serpentine to transition repeatedly between brittle and viscous behaviour. Fault zone mineralisation and seafloor serpentinisation attest to the critical role of fluids during deformation.

Deformation mechanisms documented in the STTFZ should be directly analogous to those operating in active oceanic transforms. Our field observations outlined above demonstrate spatial and temporal variations in structural styles not captured in numerical models. We aim to determine how variable conditions control deformation by further detailing deformation mechanisms via microstructural and EBSD analysis. Photogrammetry and image analysis will provide context to the microscale analysis and further quantify structural and geometrical relationships in the STTFZ. The range of observations possible in the STTFZ makes it an ideal site to study the controls on deformation style in oceanic transforms.

The Esla Nappe (Cantabrian Zone, NW Iberia): preliminary data on its basal shear zone damage and fault rock assemblages

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The Cantabrian Zone is located at the core of the Ibero-Armorican Arc and constitutes the foreland fold-and-thrust-belt of the Variscan Orogen in NW Iberia, where several thrust nappes were emplaced during the Pennsylvanian. While its large-scale structure has been studied in detail by numerous authors, the mechanisms of emplacement of the thrust nappes remain rather unexplored. Few contributions have focused on the fault rocks found at the basal shear zone of the Esla Nappe (Arboleya, 1989), and more recently, at the base of the Somiedo Nappe (Caldera et al., 2016).

With the aim of constraining the thrust emplacement mechanisms that operated at different structural levels within the Cantabrian Zone, a new project has recently been initiated at the University of Oviedo that will focus on the study of the characteristics and spatial distribution of fault rock assemblages and structures associated to nappe basal shear zones. The starting study area is the Esla Nappe, located in the inner portion of the Cantabrian fold-and-thrust-belt, and formed by a ca. 3 km-thick Palaeozoic sedimentary sequence. The nappe was translated 19 km towards the NNE, though the displacement at its leading sector was accommodated by several thrusts: once initial translation reached 6 km, displacement was transferred from the hangingwall ramp to an antiformal stack of Carboniferous limestones developed in the footwall flat, where the remaining displacement was accommodated (Alonso, 1987). This structural configuration has potentially allowed the nappe basal shear zone, mostly developed in Cambrian dolostones and limestones, to preserve fabrics formed by different finite displacements in different areas.

Preliminary observations indicate that the basal shear zone is composed by a variety of fault rock assemblages, which vary in thickness between 2 and 8 m. The assemblages include fragmented dolostones and limestones, breccias, cataclasites and ultracataclasites, which follow a strain gradient that increases towards the thrust surface. In some locations, the breccias contain abundant (over 60% mode) rounded and fractured quartz grains supported by a fine-grained carbonate matrix. The origin of the quartz has been attributed to the injection of quartz grains from underlying Upper Devonian sandstones (Arboleya et al., 1999). However, the finding of quartz sand dykes with smaller grain size, injected along imbricated minor thrusts as far as ca. 30m from the basal thrust, suggests that the fluidization and injection of quartz grains occurred at a larger scale than previously thought. The presence of cataclasite and breccia fragments originated in the basal thrust in these dykes suggests that the quartz fluidization events caused hydraulic fracturing of the hanging wall rocks, and that they occurred relatively late during the Esla Nappe translation process.

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The Pyrenean Variscan Mérens intrusion: mineralogy, timing and strain partitioning within a mylonitised root zone

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An 18 km2 area in the Eastern Pyrenean Variscan belt (Axial Zone) was mapped with the aim of establishing its tectono-metamorphic evolution. Particular attention was paid to the syn-Hercynian Mérens and Quérigut intrusions' deformation history in relation to their host rock, which are still poorly understood.

The geology of this area starts in the Cambrian or early Ordovician, when a thick sequence of marine sediments starts being deposited. Apart from pelites, several arkosic, quartzitic and conglomeritic horizons can be traced throughout the Cambro-Ordovician. These are overlain by Silurian black shales, Devonian calc-phyllites, black shales and dolomites. The Aston and Hospitalet domes' protoliths intruded into these sediments as bedding-parallel laccoliths.

The Hercynian left a complex imprint on this area. F1, which runs (sub-)parallel to S0, and Andalusite high-temperature low-pressure (HTLP) assemblages demand a pre-Hercynian extensional stage. Collision and crustal thickening are documented by N-S compressive upright, symmetrical folds, followed by dextral transpressive asymmetrical folding. After these folding episodes, strain became localised in the Mérens Shear Zone (MSZ), where syn-tectonic magmas were extensively mylonitised. Late-stage felsic magmas and Andalusite pressure shadows record a sinistral shearing stage, which marks the last recorded progressive phase of the Hercynian. Brittle deformation microtextures and normal faulting followed during orogenic collapse and were potentially active during the Alpine as well. This pattern of mountain building, thermal relaxation and orogenic collapse is reflected by the consecutive growth of sillimanite, kyanite and sericite.

This geological history mildly differs from most Pyrenean Variscan papers: extension-related HTLP metamorphism, kyanite-grade metamorphism and the Late Shear Band's trajectory around the paragneiss dome are all observations that ought to be verified by further work. Improving our understanding of this area could greatly contribute to constraining the history of the Axial Zone.

Intrasalt structure and strain partitioning in layered evaporites: insights from the Messinian salt in the eastern Mediterranean

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Evaporite-dominated units are lithologically heterogeneous as halite is interbedded with other salts, in addition to clastics or carbonates. This lithological heterogeneity creates rheological heterogeneity, as the different mechanical properties of the various rock types control strain partitioning within deforming evaporites. Determining the composition and internal structure of salt bodies is important for safe drilling through thick salt sequences, and enables us to build better velocity models that allow more accurate seismic imaging of subsalt geology. However, due to typically poor seismic imaging, and a lack of outcrop and well data, the nature of this lithological control on intrasalt deformation is poorly understood.

Heterogeneous, highly reflective, Messinian evaporites, which are shallowly buried and only weakly deformed, occur along the Levant Margin in the eastern Mediterranean. This provides us with a unique opportunity to assess how: (i) intrasalt strain varies within thick salt during the early phase of margin development; and (ii) in the context of the Eastern Mediterranean, how the intrasalt seismic-stratigraphic architecture links to the geodynamic context and evolution of this tectonically complex region.

Previous studies of the Messinian salt in the eastern Mediterranean have observed increasing strain toward the top salt, before an abrupt reduction in the overburden. The strong, competent layers embedded within the halite deform in a brittle manner, while weak, incompetent halite beds deform in a ductile manner. As the more competent beds in the evaporitic sequence are folded and faulted, multiple detachment levels develop in the encasing weaker layers. It follows that the lithological sequence exerts a control on the strain distribution within the evaporite unit as it deforms in response to gravity gliding and spreading.

We use high-quality 2D and 3D seismic reflection data to map intrasalt structural style, and horizontal and vertical variations in strain. This enables us to determine how lithological and thus mechanical heterogeneity affects the structural evolution of the salt during early stage salt tectonics. Given that salt tectonics dominates the structural development of salt-influenced rifts and passive margins, the results of this study have implications for the development of structural and stratigraphic traps in these settings.

TecTask “OpenTerminology”, a public debate regarding geological terminology for Geoscientists

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Open Terminology1 is a public wiki page promoted by TecTask2, the commission on Tectonics and Structural Geology of the International Union of Geological Sciences (IUGS). The project idea was initiated a few months ago with the aim of providing an updated and free instrument for the Structural Geology and Tectonics community, with special attention to developing countries.

OpenTerminology is a dynamic wiki page that we hope will attract discussion on commonly-used terminology, improving it where necessary. The webpage is open access and, after creating an account, the user is free to add comments on the terms that are already displayed, or add new ones; all the changes are recorded and can be easily traced. The term will be modified when the discussion has reached a substantial number of comments and improvements.

A fundamental aspect of the OpenTerminology is the hierarchy of the terms. The glossary is made under the assumption that terms have a specific hierarchy. They are part of cluster of definition such as that for example “rock” is the cluster of definition for “minerals” that is the cluster of definition of “atom”. We would like to boost the discussion on the hierarchy of this glossary more than simply display each term in alphabetical order.

It provides an open archive of terms that may be employed during scientific publication as well for educational and professional purposes. The open source and open access nature of OpenTerminology aims to provide a tool to promote the dynamic changes in geologic terminology over time. We encourage the whole geoscientist community to participate actively in this project so that the scientific vocabulary is adequately changed as ongoing research advances.

1OpenTerminology: http://www.tectonique.net/ttt/index.php?title=Main_Page
2Tectask: http://www.tectask.org

Final closure of the Paleo-Asian Ocean and terminal collision in the Central Asian Orogenic Belt: Constraints from the Beishan Orogenic Collage, Northwest China

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The Central Asian Orogenic Belt (CAOB), bounded by the Baltica and Siberian cratons to the North and the Tarim and North China cratons to the south, is the largest Paleozoic accretionary orogen in the world. The orogenic belt becomes progressively younger southwards. It is generally accepted that the CAOB formed as a result of accretion and collision of multiple terranes and the closure of the Paleo-Asian Ocean, but the timing and processes of the final closure of the ocean is controversial.

The Beishan orogenic collage, as the southernmost part of the CAOB, connects the Tianshan suture to the west with the Solonker suture to the east. It is an ideal part of the orogen to study the final closure of the Paleo-Asian Ocean.

Our detailed mapping (at a scale of 1:25,000) led to the recognition of three shear zone-bounded tectono-stratigraphic packages. The structurally lowest package comprises metamorphosed and foliated pillow basalt, gabbro, diabase and interlayered pelagic chert. It is likely related to the previously defined ca. 286 Ma Liuyuan ophiolite complex that occurs near the northern edge of our map area. The second package, structurally overlying the ophiolite package, comprises highly deformed rhyolitic to andesitic pyroclastic rocks. Three samples from package yielded U-Pb zircon ages from 292 ± 2 Ma to 297 ± 3 Ma (late Permian). Preliminary geochemical data indicate that they formed in a continental margin arc setting.

The third package, structurally highest and overlying the volcanic arc package, consists of metamorphosed and structurally imbricated clastic sedimentary rocks and marble, intruded by sheets of tonalite, granodiorite, gabbro and granite. Detrital zircon from a quartzite sample has ages ranging from ca. 856 to 2432 Ma, with major peaks at ca. 950-1130 Ma and ca. 1280-1400 Ma, and a quartz pebble conglomerate with detrital zircon ages ranging from ca. 370 to 2540 Ma has broad peaks at ca. 390-460 Ma and ca. 870-950 Ma. The Proterozoic ages indicate sources related to the Tarim craton. A felsic volcanic rock and a tonalite gneiss also yielded Carboniferous (336 ± 6 Ma) and Ordovician (459 ± 4 Ma) ages, respectively. Syntectonic gabbro, quartz-diorite and granite intrusions have U-Pb ages of 281± 2 Ma, 295 ± 3 Ma, and 285 ± 2 Ma, respectively.

Our data indicate that the Paleo-Asian Ocean was not closed until late Permian and the terminal collision involved terranes related to the Tarim craton.

The hinterland-foreland transition in the Variscan belt of Sardinia (Italy): insights from the Barbagia Thrust

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In continental collisional orogenic belts, the hinterland-foreland transition plays a crucial role in the deformation styles and in the exhumation modes of the mid-crustal rocks. The Barbagia Thrust (BT), a regional scale shear zone in the Variscan belt of central Sardinia, represents this transition. The BT, separating nappes with different deformation styles, is still poorly characterized (Carosi & Malfatti, 1995). We present new data of the BT and of the nearby tectonic units, using a multidisciplinary approach. We characterized in detail both meso- and micro-structural features, as well as, the metamorphic conditions with the aid of illite and chlorite “crystallinity” of rocks from the footwall, hanging wall and high-strain zone of the BT.

Moreover, combining different palaeopiezometer-wet quartzite flow law pairs we characterized the rheological parameters (i.e., flow stress and strain rate) present during the BT activity (Montomoli et al., 2018). Three main deformation phases were recognized (Carosi & Malfatti, 1995). After a D1 contractional deformation, a D2 related to the BT movement was associated to the development of a nearly 100 m tick high-strain zone with the development of a mylonitic foliation, Sm, at mid-crustal conditions, near the brittle-“ductile” transition. Metamorphic constrains obtained from the footwall, the hanging wall and the high-strain zone supported an epizonal metamorphism with no unambiguous trend related to the strain intensity (Montomoli et al., 2018).

Integrating our new metamorphic, deformation and rheological data, with previous ones in the geological literature helps to better unravel the long-lasting history of the nappe emplacement at hinterland-foreland transition in the Sardinian Variscan Belt.

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Combined 40Ar/39Ar and 87Sr/86Sr analyses of modern muscovites in the Narayani River catchment, Central Nepal

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It is well established that segments of the Himalayas have undergone episodic rapid erosion throughout the orogen's uplift history, but the scale of this segmented uplift remains poorly understood. 40Ar/39Ar ages for detrital muscovites from two modern river catchments, the Karnali River in western Nepal and the Narayani River in central Nepal, are distinctly different. This indicates that the scale of uplift over the past ~10 million years is smaller than the combination of these two drainage basins.

A new method is being tested in which detrital muscovites from the Narayani River catchment that have been analysed for 40Ar/39Ar are also analysed for 87Sr/86Sr. By comparing the ages of groups of muscovites with the same Ar/Ar ages (e.g. all 8 Ma grains) with their 87Sr/86Sr values, we can further constrain the scale of uplift in this area. If all of the grains for a single age group have similar 87Sr/86Sr values, we interpret a smaller area of uplift, whereas if the 87Sr/86Sr values have a wide distribution, we interpret that a larger area was uplifted at that time.

Unmixing of detrital data from the Narayani River catchment, using the Monte-Carlo method of Sundell and Saylor (2017), allows us to estimate the contribution of different tectonostratigraphic units within the catchment. Initial bedrock 40Ar/39Ar data show lateral variation throughout the catchment, consistent with the lateral variation in units and along-orogen structural features. This leads to the expectation that segmented uplift within the catchment is laterally controlled.

Coseismic extension recorded within the damage zone of the Vado di Ferruccio Thrust Fault, Central Apennines, Italy

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High- resolution hypocentral localisation illuminates the activation of seismogenic volumes dipping at low angle (< 30°) in extensional settings in the continental crust. The individuation of the geological structures and of the fault processes associated with these seismic patterns will contribute to the interpretation of seismic sequence evolution, and seismic hazard studies.

Here we report field and microstructural evidence of the seismic re-activation in extension of pre-existing contractional structures (thrusts). The Vado di Ferruccio Thrust Fault (VFTF) is a narrow fault zone in the Central Apennines of Italy, accommodating ~1 km of shortening during Miocene-Pliocene and exhumed from < 3.5 km depth. In the thrust zone, exposures within the Fornaca Tectonic Window show Late Triassic bituminous dolostones are thrust over Middle Jurassic interlayered carbonates upon a SSW-dipping fault. Isoclinal folds are dragged and sheared by thrust-parallel reverse faults in the footwall block whereas systematically-oriented faults occur within the hanging wall. Fault core observations are consistent with stable pressure solution-mediated aseismic sliding towards N024 during thrusting, with cyclic veining and faulting. Later extension has been accommodated at the regional scale by major normal faults cutting through the VFTF, while veins and pressure-solution seams crosscut the microstructures associated with thrusting and record the extensional stress regime within the thrust fault core. Lenses of shattered rocks (up to 10 m thick), cut by a dense network of small displacement (< 1.2 m) mirror-like normal faults, are reported in the hangingwall of the VFTF. These minor faults, related to a sharp principal slipping surface on the upper margin of the fault core, are interpreted as fossil evidence of microseismicity compartmentalized within the hanging wall of the VFTF. Synthetic and antithetic normal faults within the VFTF hangingwall damage zone are kinematically similar to the structures rupturing during small earthquakes (Mw < 2) in the hangingwall of low angle detachments such as the thrust flats inverted during the 2009 Mw 6.1 L'Aquila seismic sequence or the major normal Altotiberina Fault.

Structural and microstructural study of the ultra-high temperature Khondalite Belt, North China Craton

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The Paleoproterozoic Khondalite Belt (KB) in the North China Craton represents a great portion of a hot and partially molten orogenic crust that recorded large mass and heat transfers through time and space. The KB is famous thanks to the numerous occurrences of UHT metamorphism that have been reported this last decade. In comparison, very few structural data is documented along the belt. In this study, we present a detailed petro-structural analysis of the KB and give clues on its geodynamic setting and tectono-metamorphic evolution.

Rock from the KB are mainly garnet +/- spinel +/- sapphirine-bearing migmatites, garnet +/- opx-bearing I-type granites, leucocratic garnet-bearing S-type granite and gabbronorites. Our P-T quantifications performed on migmatites and granulite relics, together with P-T data from the literature, indicate that crustal anatexis and UHT metamorphism affected a large part of the orogenic crust, from 15 to 40 km deep. The partially molten rocks recorded two main deformation events, named D1 and D2. The early D1 deformation is defined by a flat-lying or weakly dipping S1 foliation that holds a N70E trending L1 stretching and mineral lineation. The D1 fabric is reworked by a dextral transpressional D2 deformation responsible for the development of F2 folds and a km-scale system of S2-C2-C'2-like pattern. The N70E trending S2 foliation is sub-vertical to highly dipping toward the south. Kilometer-scale C2 and C'2 shear zones are sub-vertical and trend N90-100E and N110-120E, respectively. At sample scale, the D1 migmatites show typical elongated garnet grains and garnet-quartz aggregates with a 1/10 shape ratio, whereas D2 migmatites show rounded garnets. EBSD investigations revealed that the D1 garnet was ductilely deformed through diffusion-assisted dislocation creep with some subgrain rotation recrystallization. This deformation mechanism followed the ½<111>(110) slip system. Quartz grains within the grt-qz aggregate are larger and show a different fabric compared to those within the matrix. Rheological modeling using power flow law is coupled to EBSD to characterized the (U)HT D1 deformation stage. We show that garnet was very weak and that the grt-qz aggregate was as weak as the quartzo-feldspathic layer during D1, with an interconnected weak layer behavior.

Our field-based analysis led to a reappraisal of the tectonic significance of the KB that we no more consider as a collisional belt in the western north china block but as a continental magmatic arc built at 1,96-1,90Ga, subsequently involved in the Trans-North China Collisional Orogeny. The coupled macroscopic and microscopic (EBSD) analysis revealed that the onset of melting at high temperature conditions (>850°C) triggered the lateral flow of the deep crust inside the arc.

Anisotropy of Volume Change and Permeability in Hard Sandstones under Triaxial Stress Conditions

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Volumetric strain and permeability are strictly interconnected properties and important controlling parameters for deformation patterns in rock masses. Under reservoir conditions, stresses may be highly inhomogeneuous and anisotropic, leading to porosity changes and consequently affecting fluid flow. Therefore, it turns out to be a challenging issue in rock mechanics to evaluate volume change based on traditional soil mechanics background, originally intended for soft materials under low and mostly isotropic pressures. In this respect, we carried out triaxial compression tests to describe the interplay between effective porosity, volume change and permeability of two hard sandstones (Rotliegend and Bunter Sandstone) by quantifying porefluid (water) volume change with fully water saturated cylindrical rock specimens (14 cm length and 7 cm radius).The greyish Bunter Sandstone (Trendelburger beds) is a silica cemented subarkose of Triassic age with an effective porosity of ca. 12 % and a hydraulic permeability of 6.7 x 10-9 m/s, whereas the red-brownish Rotliegend Sandstone (Bebertal) is a carbonate and silica cemented sandstone of Permian age, clearly less porous (ca. 6 % of effective porosity) and less permeable (3.5 x 10-10 m/s) than the Bunter Sandstone. As both sandstones are clearly layered, we consider the directions parallel and perpendicular to bedding as planes of anisotropy. Peak strength and peak compression were evaluated after the Mohr-Coulomb failure criterion, by which we observed a pronounced brittle behavior influenced by coring direction in both sandstones. Permeability and volumetric strain are also directional anisotropic. For both materials, increasing porefluid pressure leads to an earlier microcraking stage, which induces a more pronounced dilatant behaviour and therefore decreases compressive strength. In order to frame physical with mechanical properties better, sandstones were compared to rocks with pronounced plastic behaviour, such as the Opalinus Clay and Keuper mudstones (Stuttgart Formation) in the same experimental approach.

Geomechanical effects in a Bunter Sandstone due to impure CO2 injection

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The geological storage of supercritical (sc) CO2 in deep sedimentary formations has been considered as a transitional option to reduce industrial and energy related CO2 emissions into the atmosphere. As a consequence, the injection of scCO2 has chemical and mechanical effects on the host rock. The nature of these effects is not yet fully understood. Preliminary experimental investigations using the Bunter Sandstone as an analogue reservoir rock for CO2 storage have shown a great variation of effects in mechanical properties, which might be due to the lithological variation within the sample, the anisotropy effects of bedding and particularly to the interaction time among CO2 stream, brine and rock. In this abstract we proceed with this investigation considering the influence of an impure CO2 stream by assuming small concentrations (70 ppm) of SO2 and NO2. In long-term experiments lasting five weeks, we exposed rock samples (diameter = 7 cm, length = 14 cm) to scCO2 hydrostatic pressure in an autoclave system under representative reservoir conditions (T = 333 K, p = 16 MPa). By doing so, we obtained strength and deformability parameters from triaxial compression tests which could be complemented and compared for differently handled samples: pure and impure CO2 stream, inert gas stream (N2) and untreated samples. The most significant influence of an impure scCO2 treatment observed on the Bunter Sandstone was on its deformability, due to an increase of brittleness affecting its volumetric strain. Another aspect of this work considered geochemical reactions among rock, brine and scCO2 stream which are particularly effective in the pore space of the rock. An additional evaluation of porosity, pore connectivity and pore ratio was made with a rock sample before and after pure scCO2 treatment by carrying out X-ray computed micro-tomography (CT) analyses and image analyses. With this method we could detect layer boundaries by means of porosity changes and therefore characterise an irregular distribution of pore space within the sample. The CT and image analyses on the impact of scCO2 treatment were limited by the resolution of 13 micrometer, however the treatment seems to affect the layers selectively. This work is part of the joint research project CLUSTER (www.bgr.bund.de/CLUSTER), funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), which investigates the impact of CO2 streams and mass flow for different scenarios along the carbon capture and storage (CCS) chain.

Extreme Mesozoic crustal thinning in the Eastern Iberia margin: The example of the Columbrets Basin (Valencia Trough)

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Eastern Iberia preserves a complex succession of Mesozoic rifts partly or completely inverted during the Late Cretaceous and Cenozoic in relation with Africa-Eurasia convergence. Notably, the Valencia Trough, classically viewed as part of the Cenozoic West Mediterranean basins, preserves in its southwestern part a thick Mesozoic succession (locally 10km thick) over a highly thinned continental basement (locally only 3,5km thick).

This sub-basin referred to as the Columbrets Basin, represents a Late Jurassic-Early Cretaceous hyper-extended rift basin weakly overprinted by subsequent events. Its initial configuration is well preserved allowing us to unravel its 3D architecture and tectono-stratigraphic evolution in the frame of the Mesozoic evolution of eastern Iberia. The Columbrets Basin benefits from an extensive dataset combining high-resolution seismic reflection profiles, drill holes, seismic refraction data and Expanding Spread Profiles. The interactions between halokinesis, involving the Upper Triassic salt, and extensional deformation controlled the architecture of this Mesozoic basin. The thick uppermost Triassic to Cretaceous succession describes a large-scale syncline shape, progressively stretched and dismembered towards the basin borders.

The SE-border of the basin is suggested to be characterized by a large extensional detachment fault acting at crustal scale and interacting locally with the Upper Triassic decollement. This extensional structure accommodates the exhumation of the continental basement and part of the crustal thinning.

Eventually our results highlight the complex interaction between extreme crustal thinning and occurrence of a pre-rift salt level for the deformation style and tectono-stratigraphic evolution of hyper-extended rift basins.

The Tertiary pegmatite field of the Central Alps in the southwestern Bergell Pluton: timing of intrusion and implications for the local stress field

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The Central Alps host the largest field of Tertiary pegmatites of the Alps. In this study we investigate an area of the pegmatite field in the upper Valle dei Ratti, at the southwestern border of the Bergell Pluton. In the study area several sets of discordant dykes with different orientations and different features crosscut each other. The aims of the study are to (i) recognise in the field a consistent temporal sequence of sets of dykes, (ii) date each generation, and (iii) analyse the overprinting relationships between dykes and deformation structures.

Field relationships allows the recognition of four main sets of dykes (sets A-B-C-D in an oldest to youngest sequence), with different orientations and consistent mutual crosscutting relationships. The oldest set (set A) consists of aplite, pegmatite, and granite dykes constantly striking NE-SW and dipping steeply toward SE. Set B only includes peraluminous microgranite dykes, resembling the nearby Novate granite, striking approximately E-W and variably dipping toward N. Set C represents the main set of dykes, consisting of pegmatites and aplites with approximately the same orientation as set B. Set D consists of subvertical aplite dykes striking N-S. All the sets of dykes are crosscut by a steeply dipping, NNE-SSW striking set of mylonitic quartz veins. In the high-strain domains, the completely recrystallised mylonitic quartz veins show a strong bulk CPO characterised by c axes distributed in a partial YZ girdle strongly concentrated near Y, indicative of deformation temperature at least in excess of 400°C (e.g. Ceccato et al., 2017).

U-Th-Pb dating on monazites separated from pegmatite and microgranite dykes gives the following results. Set A yields four concordant ages between 34 and 27 Ma, and Tera-Wasserburg diagrams show lower intercepts of 29 and 27 Ma. Set B yields three concordant ages at 33, 32, and 27 Ma, and an alignment in the Tera-Wasserburg diagram with a lower intercept at about 27 Ma. Set C and D yield several concordant ages all between 25 and 26 Ma.

Sets of pegmatite dykes can be used as tectonic markers: their orientation and deformation features potentially record the tectonic evolution of this area of the Central Alps after the emplacement of the Bergell pluton. In general dykes open against the minimum compressive stress and propagate on a plane perpendicular to it. Our data suggest that the local minimum compressive stress shortly after the emplacement of the Bergell pluton was approximately oriented in a N-S direction and migrated toward the E-W direction at about 25-26 Ma. The whole swarm of dykes in the Valle dei Ratti area was intruded before 25 Ma at an ambient temperature above 400°C.

Ceccato, A., Pennacchioni, G., Menegon, L., & Bestmann, M. (2017). Crystallographic control and texture inheritance during mylonitization of coarse grained quartz veins. Lithos, 290, 210-227.

The microstructural record of a ‘brittle-ductile transition'

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The Calamita Schists (Elba Island, Italy) are the host rocks of the buried Porto Azzurro pluton. Contact metamorphism, related to pluton emplacement, occurred at pressures of 0.18-0.20 GPa and temperatures exceeding 650 C, lasting less than 1 Ma. Contractional deformation, coeval with high temperature metamorphism, led to the development of mylonitic shear zones in the Calamita Schists. Deformation outlasted cooling of the aureole with the development of non-Andersonian faults overprinting the mylonitic fabric.

In order to investigate the switch in deformation mechanism during temperature decrease at constant pressure (P<0.2 GPa), a sample of mylonitic quartzite with S-C’ fabric was examined by Electron Backscatter Diffraction (EBSD), optical microscopy and Scanning Electron Microscopy (SEM). The mylonitic fabric is marked by synkinematic biotite + cordierite + andalusite + K-feldspar assemblage, replaced by retrograde white mica + chlorite.

Quartz microfabric is defined by coarse-grained (100-900 µm) quartz porphyroclasts wrapped by ribbons of dynamically recrystallized finer grains (~50 µm) characterized by a strong CPO. This fabric is cross cut by conjugate and synthetic C’-shear bands localized in porphyroclasts and marked by recrystallized fine grains (5-50 µm).

EBSD data indicate that prism <a> was the dominant slip system during crystal plastic deformation in the polycrystalline ribbons. Subsequently, brittle deformation localized along intracrystalline bands (both in conjugate sets and parallel to C’ shear bands) within quartz porphyroclasts. The bands evolved in localized cataclastic micro-shear zones and in shear fractures, which localized fluid infiltration and healing by solution precipitation. The quartz new grains filling the bands are preferentially oriented with their c-axis parallel to the shear band boundary.

This work highlights that deformation in the Calamita Schists switched over time from high-temperature dynamic recrystallization, accommodated by prism <a> slip to low grade brittle-ductile processes. At the brittle-ductile transition strain partitioning was controlled by grain size and fluid penetration and was characterized by cyclical ductile-brittle mechanisms. In particular brittle failure localized in coarse-grains acted as the precursor for ductile C’ shear bands.

Kinematics of the flow in the Cavalaire Fault (Maures Massif, SE France): correlation with the transpressional Posada-Asinara shear zone in northern Sardinia

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The Maures–Tanneron Massif (MTM) is the southernmost branch of the Variscan Belt in France (SCHNEIDER et al., 2014). It was separated from the Corsica-Sardinia block because of the anticlockwise rotation related to the opening of Mediterranean back-arc basin during Miocene. Microstructural studies, kinematics of the flow and finite strain analyses were performed on mylonites from the Cavalaire Fault, a ductile Variscan regional-scale shear zone cross-cutting the Maures Massif developed during amphibolite-facies metamorphism. Kinematic vorticity analysis was performed applying the C' shear bands method (KURZ & NORTHRUP, 2008). The estimated kinematic vorticity number (Wk), varies from 0.40 to 0.68, with a mean value of 0.47. These values are indicative of a percentage of pure shear ranging from 66 % to 52 % consequently simple shear is variable between 34 % and 48 %. The angle θ, between the maximum Instantaneous Stretching Axis (ISAmax) in the horizontal plane and the shear zone boundary, was calculated. All samples fall in the field of pure shear-dominated transpression. The finite strain analysis, with the center-to-center method, was performed on an oriented sample of garnet-bearing micaschist collected within the mylonitic belt on the XZ and YZ planes of the finite strain ellipsoid. Garnet porphyroclasts, showing a homogeneous distribution, were used as strain markers. Combining the Wk value and finite strain parameters, we calculated the percentage of shortening perpendicular to the mylonitic belt, nearly 30%, and the percentage of stretching parallel to it, nearly 41%. The structural asset of the Cavalaire Fault and its metamorphic evolution are very similar to the structural setting of the Posada-Asinara shear zone in the Sardinian Variscan basement (CAROSI et al., 2012; SCHNEIDER et al., 2014). Both shear zones are characterized by a transpressional deformation with the same kinematic and developed during anfibolite-facies metamorphism. The new data about finite strain and kinematics of flow of the Cavalaire Fault strengthen the correlation between it and the Posada-Asinara shear zone in northern Sardinia (CAROSI & PALMERI, 2002; CAROSI et alii, 2012).

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Accommodation of a compression continental crust: Analogical modeling of the Tunisian Atlas

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Tunisia lies at the eastern end of the Maghreb Alpine chain. It is divided into two major structural domains which belong to the outer zones: the Tellian domain in the north and the Tunisian Atlas further south. Two oceanic areas border Tunisia: the Algero-Provencal basin opened in a back arc position during the Miocene in the north and the Ionian Sea, a relic of the Tethyan oceanic domain now subducting below the Calabria and the Mediterranean ridge in the East.

The formation of the Maghreb alpine chain occurred during Cenozoic time. In the external zones, the deformation, dated from the Tortonian to the actual, is characterized by the association of compressive, strike-slip and extensive structures. NE-SW oriented folds and thrusts affect the Mesozoic cover. Particularly abundant in the Tell and the North of the Atlas, these structures are more scarce towards the south where they interact with two conjugated strike-slip corridors: the Negrine-Tozeur and the N-S axis fault zones. Late, extensive structures compatible with directions of NE-SW then NE-SW extension are set up in the Tell and Northern Atlas zones.

The objective of this study is to replace this association of structures in a broader geological context and provide better constraints to deep-seated structures. For this, an analog modeling approach has been adopted.

The experimental device includes a 60/60 cm PVC box. It is subjected to shortening simulating the convergence between the Eurasia and Africa plates and extension in a direction, orthogonal to the compression, which represents a free edge located at the level of the Mediterranean ridge. This box is filled with layers of deformable materials: sand for brittle levels, upper crust and sedimentary cover and silicone to represent the ductile levels such as, lower crust and Triassic evaporates.

Several experiments were carried out by changing the initial geometry of the model (presence or absence of detachment levels) and the physical parameters (deformation speeds). The results show that the presence of a level of detachment at the base of the sedimentary series is necessary to correctly represent the compressive and extensive structures in the central Atlas and north of Tunisia respectively. Similarly, a free edge perpendicular to the direction of compression allows the formation of strike-slip and conjugate structures similar to the fault of Negrine-Tozeur and the N-S axis. These experiments suggest that the main strike-slip structures and thrusts located north of Tunisia rooted in the crust whereas normal fault to the north and reverse structure to the Tunisia affect only the sedimentary cover.

Keywords: Accommodation, compression, Analogical modeling, Tunisian Atlas, strike-slip corridors.

Along-strike fold shape and deformation style variability in a multiphase fold evolution: insights from the Pag anticline, External Dinarides, Croatia

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In this contribution, we describe the preliminary results of a structural study carried out in the Pag anticline, a 30 km-long fold well exposed in the homonymous island, in the External Dinarides (Croatia). It represents a good field analogue for folded and faulted tight-carbonate reservoirs and has been studied by combining different techniques and observation scales, including drone photogrammetry, structural analysis, and microstructural and petrographic observations. The Pag anticline involves about one km of Cenomanian to Senonian well layered rudist-bearing platform carbonates, overlain by 250 m of Ypresian Foraminiferal limestones and by an Eocene clastic thrust-top basin. In cross section, the Pag anticline shows an asymmetrical box-type geometry, with steeply-dipping to overturned limbs and a wide flat crestal zone. The fold is dissected by minor thrusts and backthrusts, and by two main sets of sub-vertical strike-slip faults oriented N-S and E-W, respectively. The forelimb is very continuous along strike, and is characterized by bed dipping 60-70° to the SW in the northern sector of the island, passing gradually to vertical and overturned beds towards the southern sector. In contrast, the backlimb shows a higher structural complexity. In the northern sector, the gently NE-dipping crestal zone is thrusted over the NE limb through a low angle backthrust dipping to the N, associated with a kilometre-scale footwall syncline. Deformation in the footwall of the backthrust is accommodated by minor footwall splays. In the central part of the fold, where the lowermost structural level crops out, deformation is expressed by the development of a hectometric triangle zone. The transition from the backlimb to the crestal area consists of a wide deformation zone characterized by indentation and passive-roof thrusting, with associated limb rotation. Moreover, because of the lack of weak mechanical interlayers, bedding-parallel shear is mainly accommodated by development of minor thrusts and backthrusts, diffuse veining, and pressure-solution cleavage development, arranged in “proto S-C type arrays”. From north to south, the backthrust-dominated fold architecture passes to a forethrust-dominated geometry through an overlap zone characterized by a narrow complex area where deformation is mainly expressed by strike-slip faults bounding rotated blocks about vertical axes and compartmentalizing fold geometry into sectors with different amounts of fold tightening. At outcrop- to micro-scale, fold- and fault-related deformation patterns consist of complex arrays of veins and stylolites that formed both before and during fold and fault development. Multiple sets of stylolites and narrow cataclastic stripes predominate in thrust damage zones, while strike-slip fault damage zones are characterized by cataclastic breccia zones with evidence for hydrofracturing. Different deformation events are recognized, from pre- to late-folding. Our results indicate that progressive fold tightening and differential amounts of rotation about vertical axes during multiple deformation events produce structural style changes and related deformational patterns at different scales. Deformational style transitions are accommodated in sectors characterized by high structural complexity, which strike near perpendicular to the fold axis. All this structural complexity, which is typically overseen in seismic data, may be very common in buried hydrocarbon reservoirs in folded platform carbonates and may significantly influence fluid flow and storage.

Structural development of the Shimanto Belt, SW Japan—based on analysis of Prelithification shear deformation of melange

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The Shimanto Belt is distributed along the Pacific side of southwest Japan. Melange in the upper Cretaceous Shimanto Belt, Wakayama Pref., represent a significant component of earliest deformation structures due to sinistral strike-slip shear. Study area of melange are two coastal area (Shiohuki-iwa, Karakozaki) and a inland area (channel of the Hidaka river), respectively, correspond to Miyama accretionary complex and Ryujin accretionary complex. Detailed analysis of sedimentary facies and structures in melange, the upper Cretaceous, the Shimanto Belt, together with regional field mapping, provides to understand the primitive shear deformation during sedimentary rocks were unconsolidated. Brittle-ductile deformations of rocks associated with later faulting than former shearing were also studied.

The melange is composed of lenticular sandstone and varicolored mudstones which are surrounded by sheared argillaceous matrix. Intensely disrupted stratification is dominated by asymmetric structure. Composite planar fabric in each melange results from sinistral sense of shearing. Based on observation in the outcrops, melange is structurally divided into Y-shear zone (YSZ) and P-foliation zone (PFZ). Shearing-related YSZ consists of thick lenticular sandstone (strikes subparallel to a direction of shear), intense shear band (thin layer with concentrated prelithification shear deformation) and varicolored mudstone dominant melange. The PFZ consists of lenticular or curved sandstone (strikes slightly oblique to a direction of the YSZ) and mudstone dominant melange (associated with foliations which slightly oblique to a direction of the YSZ). Preserved radiolarian fossils from the YSZ supports that the deformation was formed under a prelithified condition.

Accretionary prism of relate forearc-trench system (i.e. Nankai Trough) has been immensely studied with seismic prospecting profile and deep sea drilling. It is widely accepted that the Shimanto Belt is one of the most preserved early deformation of accretionary processes of oceanic plate subduction. However, the melanges in the investigation areas underwent sinistral sense of shear during sediments were prelithified. Consequently, sinistral strike-slip shear under prelithification shear deformation extensively pervade throughout the upper Cretaceous Shimanto Belt. Melange represents deformation of prelithified state is identical with a result that the Shimanto Belt is formed by sinistral strike-slip motion in arc-trench system, and supports the structural evolution of the Shimanto Belt. (Taira, 1988),

Tectonic Compartmentalisation of Braided Fluvial Systems using Digital Outcrop Models

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The application of UAV-collected digital outcrop model (DOM) investigation is quantitavely evaluated using a set of fluvial case studies to determine distribution, offset intensity and barrier-baffle properties of reservoir interval faults and fractures within braided fluvial systems, and attempts to quantify the metrics of such reservoir compartmentalisation. Here, DOMs are used to populate reservoir compartmentalisation for a given depositional system, and demonstrate petrophysically any effects these features may have on ultimate fluid recovery.

Data collection techniques are examined to demonstrate their utility for collating measningful and reliable statistical information needed to build tectonic process-controlled reservoir models. Quantifiable accuracies are required to build a large geostatistical dataset and evaluate common compartmentalisation metrics of braided fluail system deposits, derived from a suitle of case studies. Typical data collection methods are largely restricted by ease of access, or to using remote obvservations with limited accuracies, such as photographic methods. Digital data collection techniques such as Lidar, RTK GPS, UAV-mounted Structure-from-Motion photogrammetry and Hyperspectral imaging allow more accurate measurements to be taken, from previously inaccessible locaitons. High density, classified point clouds and phogrammetric models were generated in Agisoft Photoscan Pro, before being statistically interrogated in Virtual Reality Geoscience (VRGS). This generated many more measurements, as the area from which accurate data can be extracted is increased, providing a more meaningful statistircal dataset and reducing uncertainty in the final reservoir model.

Case studies of the carboniferous Millstone Grit Group, UK, Triassic Sherwood Sandstone Group, UK and Late Triassic Wolfville Formation, Nova Scotia, CA are all well-developed braided fluvial systems, widespread within basinal depocenters. Quantitative data comparisons of all scales of tectonic features and relative facies within which they occur across an entire braided fluvial system provide robust metrics for reservoir model populaiton, and inter-well prediction. In all cases, periods of tectonism are concentrated within ‘inter-fault’ -and fracture- zones, reducing statistical propabilities of finding similar structures elsewhere in the braidplain sediments at that given time. Dynamic flow properties of such damage zones show little internal petrophysical organisation, being both baffles and conduits to flow; complete barrier systems are scarce in near-clean-sand strata. The results provide a statistical, three-dimensional framework to interrogate and predict braided fluvial system compartmentalisation more quantatively, to guide subsequent reservoir modelling processes based on metrics and tectonic process, rather than architectures alone. These case studies show how UAV data collection is invaluable to more completely assess reservoir intervals, at greater speed, with more accurate results for quantifying and predicting structural distribution within braided fluvial systems.

Re-interpretation of the INDEPTH deep seismic profiles (Himalaya)

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The project INDEPTH (INternational DEep Profiling of Tibet and the Himalaya) was an interdisciplinary programme led by the Cornell University. Its first two stages in 1992-1995 imaged the deep crust of the Himalaya and southern Tibet, using seismic reflection. The interpretations and models published by the INDEPTH working group have been fundamental for understanding the overall structure of the mountain belt. The INDEPTH data remain the only deep crustal seismic reflection images from the area, a situation that is unlikely to change in the foreseeable future.

Crustal seismic data, including INDEPTH, are conventionally interpreted by connecting strong amplitudes of distinct reflections. The connected strong reflections are interpreted as geological boundaries that may or may not be structural in nature. At the same time, many structural boundaries within the crust lack the acoustic impedance contrast to produce sufficient reflectivity. As a consequence, relying on interpretation of strong reflections only allows for partial interpretation of the data. The interpretation can be enhanced by including the distributed reflection patterns throughout the seismic image in the interpretation. These patterns can be analysed and emphasised with seismic attributes. The development of seismic interpretation software has made it possible to easily combine the pattern interpretation method with pattern enhancement, and to map the interpreted pattern distributions in 3D. We use the method of pattern interpretation to gain more detailed information from INDEPTH data, and to produce a new structural interpretation of the Himalaya and southern Tibet.

The new interpretation shows several enhancements to the previous large-scale interpretations. For example, the Kangmar Dome metamorphic “core complex” is associated with a hanging-wall fold above a thrust sheet. Furthermore, there are no indications that the much-debated South Tibetan Detachment. is the same extensional structure at Wagye La (just south of the Kangmar Dome) as at Zherger La (at the southern margin of the Tethyan Himalaya). These and other details of the new interpretations may challenge some aspects of the present tectonic models for Himalaya.

Influence of rift-inheritance on mountain building processes: a point of view based on the Western Pyrenees and Western Alps

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The relative role of subduction/collisional processes and rift-inheritance in controlling the formation of the deep structure of orogens has been investigated. We use the Western Pyrenees and Western Alps as case studies as both recently benefited from the acquisition of high-resolution tomographic transects. Despite different compressional histories, their overall present-day deep structures appear comparable, characterized by a deep orogenic root and a well-imaged indenter. Apart from uncertainties on the initial width of the two systems, their rift-related architecture shared many similarities, comprising formerly severely thinned continental crust, exhumed subcontinental mantle and minor magmatic additions. Remnants of these hyperextended domains occur in the internal parts of both orogens, as observed on regional maps of the former Pyrenean and Alpine Tethys rift systems.

Based on the analysis of the nature and depth of potential decoupling levels in analogous present-day hyperextended rifted margins, we appraise their role in building Alpine-type orogens. Focused along the high-resolution tomographic transects, we consider the implications for the interpretation of orogenic roots nature and structure and the consequences on restorations compared to previous interpretations. Despite contrasted nature of indenters, we show that their role in controlling the final stage of collision and present-day deep structure is likely comparable.

Our two examples reflect a variability in the role of rift-inheritance. If the Pyrenees seem to represent one extreme, where rift-inheritance is important at various stages of convergence, in the Alps the role of rift-inheritance appear subtler, mainly restricted to the pro-wedge of the orogen during the final E-W convergence.

Slow earthquake phenomena – perspectives from subduction mélange exposed on Kyushu Island, Japan

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Geodetically detected slow slip (transient aseismic creep), and seismically detected tectonic tremor (noise-like low-frequency signals) occur near the plate interface in subduction zones and are interpreted to arise from megathrust shear displacement. Major questions remain regarding the physical processes and deformation mechanisms that control these phenomena in particular, and the rheology of the subduction megathrust in general.

On Kyushu Island in SW Japan, exhumed tectonic mélanges record deformation during Cretaceous subduction at grades from prehnite-actinolite to blueschist facies. We present results of work on mélange from three locations on Kyushu Island, representing three different levels of exhumation. Coastal Makimine mélange contains prehnite-actinolite facies metapsammite and metabasite clasts within a pelitic matrix. Inland Makimine mélange contains greenschist facies dolerite and metapsammitic and metapelitic schists. In the Nishisonogi metamorphic rocks on Nishisonogi Peninsula, blueschist facies metabasites and metasediments are enveloped by ultramafic shear zones.

In coastal Makimine, quartz and chlorite precipitates fill brittle fractures in vein swarms, and metapsammite and metabasite clasts are locally elongated. Pressure solution seams are common in metapelite both here and in inland Makimine. In inland Makimine, metapelite and metapsammite are well lineated and bulging recrystallization of vein quartz has produced 10 µm subgrains. Intense L-S tectonite fabrics occur in metasediments and metabasites from the Nishisonogi Peninsula and grain boundary migration has produced ~60 µm quartz grains. Localised serpentine-actinolite-chlorite shear zones contain well developed S-C fabrics, scaly fabrics, and quartz veins.

Pressure solution in metapelite and low strains recorded in metapsammite and metabasite clasts from coastal Makimine suggests pressure solution in metapelite controls mélange rheology shallower than the quartz brittle-viscous transition. Deeper than the quartz brittle-viscous transition, dislocation creep of quartz and pressure solution in metapelite likely control mélange rheology. In the blueschist facies, well developed deformation fabrics in localised ultramafic shear zones suggests these features exert significant control over mélange rheology. Quartz veins at all localities attest to local discontinuities within a viscously deforming mélange; we suspect that the formation of these veins represents a tremor sourced.