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Abstract Volume

Pre-Alpine stratigraphy and structural architecture of the Monviso meta-ophiolite Complex (Western Alps)

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The Monviso meta-ophiolite Complex (MO) represents a major eclogitized remnant of the Ligurian-Piedmont oceanic lithosphere stacked in the Western Alps, and, despite the overprint of subduction- and collisional-related metamorphism and tectonics, displays records of its oceanic history. The tectonostratigraphy of the MO is characterized by the occurrence of a major shear zone (i.e., the Baracun Shear Zone, BSZ) that, all along the Complex, separates massive serpentinite and metagabbro (i.e., the footwall of the BSZ) from metabasalt and metasediments (i.e., the hangingwall of the BSZ).

The up to 1 km thick massive serpentinite derives from lherzolite and harzburgite, and hosts widespread bodies of Mg-Al-rich metagabbro with dykes and pods of Fe-Ti-rich metagabbro and metaplagiogranite. The massive serpentinite, at the top, is discontinuously overlain by meters thick horizons of meta-ophicarbonate. The metabasalt ranges in thickness from tens of metres to several hundreds of metres, and includes fine-grained aphyric metabasalt, pillow metalavas and volcanic metabreccia. The metasediments consist of two different successions: the lower one rests below or interfingered with the metabasalt and consists of calcschist interbedded by metasandstone and metabreccia of gabbroic composition (i.e., the syn-extensional succession); the upper one unconformable overlains both serpentinite, metagabbro, metabasalt and syn-extensional metasediments, and consists of quartzite, withish marble and calcschist, which is devoid of ophiolite-derived material and is interbedded by layers of marble and quartz-rich schist (i.e., the post-extensional succession).

The BSZ consists of mylonitic talcschist and serpentine schist embedding meters sized blocks of metagabbro, which were unconformable sealed by post-extensional sediments. The BSZ never contains blocks of metabasalt and syn-extensional metasediments, and has been interpreted as a remnant of an intra-oceanic detachment fault, which controlled seafloor spreading and extensional tectonics in a Late Jurassic oceanic core complex.

The oceanic history of the MO evolved through four main stages, which correspond to (*i*) a first magmatic event of late Middle Jurassic age (163±2 Ma), with emplacement of gabbroic plutons into the lithospheric mantle, (*ii*) a main tectonic event of lithospheric-scale extension, with detachment faulting and exhumation of mantle rocks, (*iii*) a second magmatic event of Late Jurassic age (152 ±2 Ma), with emplacement of plagiogranite, eruption of basaltic lava flows and deposition of ophiolitic detrital sediments, and (*iv*) a final stage marking a magmatically and tectonically quiet episode in the history of the Ligurian–Piedmont Ocean, with deposition of chert, limestone and turbiditic sediments which sealed the rugged seafloor topography.

Ductile shearing on top of the Eocene extruding wedge: the Combin Shear Zone

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A popular model for the exhumation of HP-UHP rocks is the 'extruding wedge' model, where a crustal slice is bounded at its base by a 'thrust shear-sense' fault and to the top by a 'normal shear-sense' fault. In the Western Alps, three main 'normal shear-sense' shear zones may have bounded extruding wedges at different times during the Alpine orogeny, namely the Late Cretaceous-Palaeocene Fobello-Rimella Shear Zone during extrusion of the Cretaceous Sesia-Dent Blanche stack, the late Eocene Combin Shear Zone during extrusion of the Briançonnais-Piemonte-Liguria ('Penninic') stack, and, finally, the Frontal Penninic Fault during Oligo-Miocene extrusion of the Helvetic stack.

The available knowledge on the Combin Shear Zone (CSZ), the best exposed of these three shear zones, will be reviewed based on a synthetic structural map of the NW Alps. A general agreement has been achieved on the following points.

1. Geological mapping has established the geometry and continuity of the CSZ from the frontal part of the Dent Blanche Tectonic System to the western boundary of the Sesia Zone.
2. The CSZ has been cut during the Miocene by the brittle Aosta-Ranzola Fault, with an estimated downthrow of the northern block of c. 2.5 km with respect to the southern block. As a consequence, the sections observed north (Monte Rosa) and South (Gran Paradiso) of the Aosta Fault display different structural levels in the Alpine nappe stack.
3. The CSZ has been folded (Vanzone phase) during the final part of its history (i.e. when displacement along the CSZ was no more taking place), due to the indentation of the Adriatic mantle. This offers us the unique opportunity to study the change in deformation mechanisms along the shear zone (for a distance parallel to its displacement of about 50 km).
4. The main ductile deformation along the CSZ was taking place at greenschist-facies conditions, overprinting eclogite-facies to greenschist-facies deformations of Cretaceous to Middle Eocene age.

More controversial are the following issues.

5. The thickness of the ductile shear zone increases from NW (frontal part of the Dent Blanche) to SE (frontal part of the Sesia Zone), from a few hundred metres to several kilometres. The type of lithologies pervasively reworked by the ductile shear changes along strike (dominantly calcschists from the topmost oceanic units in the Combin Zone, possibly up to the whole of the 'gneiss minuti' in the frontal Sesia Zone).
6. A major consequence of the ductile displacement along the CSZ is the development in its footwall of south-east-verging, kilometre-scale, folds (Mischabel phase). The sedimentary sequences of the Pancherot-Cime Bianche-Bettaforca Unit may be used to estimate the minimum amount of 'normal shear sense' displacement of the order of 15-20 km.
7 The CSZ is cutting and reworking eclogite-facies structures developed in its hangingwall (Sesia) as well as in its footwall (Zermatt). Two examples of kilometre-scale overprinting structures (Ollomont and Cignana) will be discussed in detail.

Mass transport through diffusion in a stationary fluid: example from veins associated with fossil hydrothermal systems, Adamello and Bergell plutons (central Alps)

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Fluid flow is an important mechanism associated with heat and mass transport within the Earth's crust. Studying veins in particular can be key in understanding fluid movements, unravelling fluid composition, its origin, and paleo stress regimes. Veins are ubiquitous in Alpine metamorphic rocks. They are typically surrounded by selvage zones, indicating mass transfer related to the fluid-rock interaction. Different formation mechanisms have been suggested, ranging from the local phenomenon, where the veins are buffered by the surrounding host-rock requiring only limited fluid movement or infiltration, to the veins representing major fluid escape pathways on the km-scale. In most regional metamorphic environment there is no unique solution to constrain the fluid flow since three-dimensional geometry of the vein systems is often not available at the outcrop scale; in addition, the tectono-metamorphic history is typically prolonged and complicated. Hence, it is not surprising that contact metamorphic environment have been studied in much more detail from a mechanistic point of view. Here we present a detailed geochemical study on well-known hydrothermal veins and explore their significance for regional metamorphic environements.

Veins in contact metamorphism are typically associated with significant mass transfer. That is the case for the veins forming through fluid infiltration of magmatic origin in dolomitic marbles at the contact with the Bergell and Adamello intrusive rocks (Central Alps, Italy). They have a central fracture, which is framed by relatively symmetric and extensive reaction zones, where the dolomite has been completely replaced by new silicates and calcite. An advantage of studying these veins is the large chemical and isotopic disequilibrium between the magmatic fluids and the carbonates, which simplifies the tracing of fluid processes and mass transport. They are also well exposed giving access to the geometry of the system and allowing to better constrain fluid movements around the intrusion.

From our study, combining field observations to stable isotopes, chemistry, and phase petrology, we favour a mechanism where mass transport occurs through element diffusion in a stationary fluid over a one-pass flow-through model. Based on X_{CO2}- constrained mass balances, relatively small amount of fluids would be required, which could originate from the intrusive rocks in vicinity of the xenoliths. We show that diffusion of elements in a fluid, especially in a vein where porosity is not hindering the transport, can be a very efficient for metasomatic processes, not only orthogonally, but also along the main direction of the vein. Such mass transfer mechanism may also operate on the regional scale, and could explain extensive mass transfer even with limited fluid flow. The meter wide, greenschist facies albite-carbonate veins forming in eclogites of the upper Täsch valley (Zermatt area) are re-investigated in the light of these new ideas.

Cenozoic magmatism in the Alps and the relation to geodynamics: A review

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We summarize more than half a century of investigations on the chemical and isotopic compositions and on geochronological data of the Cenozoic magmatic rocks in the Alps and neighboring regions. Based on the tectonic units hosting the magmatic rocks and on their age and chemistry we distinguish the following groups: (A) Periadriatic magmatic rocks: calc-alkaline series between ~42 and 30 Ma, located in the immediate vicinity of the Periadriatic Fault; (B) Sesia Zone magmatic rocks: ultrapotassic, shoshonitic and calc-alkaline rocks between 33 and 30 Ma; (C) Dykes and stocks of the Southern Alps: basalts, andesites with ages bracket between 64 and 33 Ma; (D) Esterél magmatic province: basalts, andesites and dacites with mantle signature developed between 40 and 20 Ma; (E) Veneto volcanic province (nephelinites, basanites and alkali basalts between 52 and 30 Ma); (F) Volcanic and plutonic rocks at the Alps-Dinarides-Pannonian junction with agesyounger than 18 Ma; (G) Veins, dykes and stocks related to local, crustalmelting in the Central Alps (Novate granite), (H) Southern foreland related volcanic rocks (Mortara volcano, ~28 Ma).
The Periadriatic magmatism requires significant melt production and ACF processes. This is only possible by infiltration of fluids in the mantle wedge and the lower crustand a change of P-T conditions in the mantle. Their calc-alkaline character is related to Na-dominated input in the mantle and crust, which is commonly inferred to result from subduction of oceanic units. Ultrapotassic melts in the Sesia-unit most likely result from infiltration of K-dominated fluids, related to dehydration of continental material.
It is difficult to invoke one and the same geodynamic process to explain all these magmatic provinces. Magmatism at both ends of the chain, in the Esterél and at the Alps-Dinarides-Pannonian junction are probably caused by along strike changes in the geodynamic–frame of the Alpine orogeny. The Veneto volcanic province is suggested to be related to local, E-W extension in the upper plate of Alpine subduction.
Interpreting the geodynamic setting of these magmatic provinces requires the assessment of their position in map view at the time of their emplacement, hence, retro-deformation of Alpine collisional shortening in map view. This shows a different map-view distribution of magmatic bodies, suggesting a significant distance between the Eocene magmatism of the Southern Alps and the Periadriatic magmatism. No simple age trend can be observed in map view. This indicates the transition from a more distributed Eocene, subduction related magmatism to later one whose ascent and emplacement is controlled by the collisional crustal structures.

Distributed shortening in orogens (Alps, Pyrenees, Caledonides): thermicity, inheritance, and rheology

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Distributed shortening, such as diffuse faulting, penetrative foliation, distributed shear zones, is often mapped in orogens. However, these ubiquitous deformations are rarely well characterized in terms of timing and amount of shortening accommodated relatively to more localized deformation. Yet, such data may provide important constrains on the crustal rheology in collisional orogens. Here, we present published and new data on such distributed phases of shortening in various orogens. In the Alps, distributed shear zones have been mapped and dated back to ca. 30-20 Ma. During this time, the rocks followed an isothermal phase, suggesting a very slow exhumation. After this phase, the shortening localized on frontal crustal ramps which exhumed the wedge. In the Pyrenees, a long, diffuse slow exhumation period took place in the Axial Zone (70-40 Ma) before the exhumation accelerated linked to the activity of frontal crustal thrusts. In the Scottish Caledonides, where deep parts of an orogen crop out, such shortening/exhumation sequence is also suggested by geochronologic data although the duration of the metamorphic peak and the amount of shortening are less well constrained. These data show that beyond important specific characteristics (particularly in terms of inheritance) the different orogens probably share common characteristics in terms of mode and timescale of shortening that may witness the crustal rheology.

Structural and paleofluid evolution during and after the growth of the Parmelan Anticline, Bornes Massif, Western Alps

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In the northern Subalpine massifs and in the Belledonne area, a regional dextral transpression is active since late Neogene times and produced NE-SW en-echelon dextral and NW-SE sinistral faulting. In the Bornes Massif (the northernmost Subalpine massif) and in the neighboring areas (Annecy-Bonneville), well-documented seismic activity (e.g. Grand-Bornand 1994; Epagny 1996 earthquakes) indicates that this strike-slip-dominated stress regime is still active nowadays in this region of the Western Alps. Despite this geodynamic configuration has been investigated in several recently published seismotectonic studies, no geometric and kinematic data were presented to constrain at the mesoscale the complex deformation pattern resulting from the superposition of such transpression-related structural assemblage (formed in response to an E-W-striking σ_1) onto the older deformation pattern developed during a long-lasting, mainly compressional, history (dominated by a NW-SE-striking σ_1). In this contribution, we present the reconstruction of the deformation pattern in the Parmelan anticline, the more external structure of the Bornes Massif. For this purpose, we combined detailed field mapping and structural data with microstructural, petrographic, geochemical (stable carbon and oxygen isotopes) and microthermometric analyses of calcite-filled tectonic veins sampled in the Lower Cretaceous Urgonian Limestones. The NE-SW trending Parmelan anticline is a box fold characterized by steeply dipping limbs separated by a wide flat-lying crestal plateau. Fold limbs were localized by inherited pre-folding extensional fault zones. The oldest structural assemblage includes transversal calcite fibrous veins, frequently forming conjugate en-echelon arrays, and conjugate subsidiary reverse faults with associated horizontal veins, interpreted as part of a well-developed pre-folding deformation pattern formed under NW-SE layer-parallel compression. These calcite-filled veins as well as different sets of syn-folding deformation structures have oxygen isotopic values of - 8‰ <δ18O V-PDB <-2 ‰and carbon isotopic values of 0‰< δ13C V-PDB <+2‰ very similar to those displayed by the host-rock, thus suggesting a dissolution-re-precipitation process active in a closed and rock-buffered system. During late-stage transpression, the (re)activation of NNW-SSE and ENE-WSW strike-slip faults produced a pervasive post-folding deformation assemblage including oblique (with respect to the fold axis) E-W veins with associated N-S stylolites. Oxygen isotopic values of –17 ‰<δ18O V-PDB <-11 ‰of vein and fault breccia cements indicate that late-stage fault zones acted as high-permeability pathways for more 18O-depleted mineralizing meteoric fluids, possibly mixed with subsurface waters. According to our microthermometric data and assuming a mineralizing fluid in thermal equilibrium with the host rock, we can speculate that the opening of the paleofluid system, caused by post-folding regional transpression, started under maximum burial temperature (70-90 °C) and progressed during exhumation of the Parmelan anticline.

Polyphase fold-and-thrust tectonics in the Belluno Dolomites: new mapping, kinematic analysis, and 3D modelling reveal superposition of Dinaric and Alpine deformations

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The Belluno Dolomites fold-and-thrust belt represents the retro-wedge - active mainly in the Miocene - of the Eastern Alpine belt. It is still a matter of debate, however, whether Oligocene deformations related to the Dinaric belt can be recognized in this area, resulting in an interference between the two belts. We have tackled this problem in the Vajont area, where a sequence of Jurassic, Cretaceous and Tertiary units have been involved in multiple deformations.
Geological mapping and detailed outcrop-scale kinematic analysis allowed us to characterize the kinematics and chronology of deformations, which are tested in a 3D geological model. Relative chronology was unravelled thanks to diagnostic fold interference patterns and crosscutting relationships between thrust faults and thrust-related folds.
The onset of contractional tectonics post-dates the Eocene Erto Flysch, whilst in the Mesozoic tectonics was extensional (including large normal faults active in the Cretaceous). Two contractional deformation phases (D1 and D2 in the following) can be recognized. Classical top-to-S Alpine transport directions and E-W fold axes characterize D2, already recognized in previous studies and attributed to Miocene Alpine deformations. On the other hand, N-S fold axes and top-to-WSW transport directions, compatible with Dinaric deformations, characterize D1.
The 90° rotation of the regional-scale shortening axis between D1 and D2 results in complex thrust and fold interference and reactivation patterns. For instance a km-scale N-S trending D1 syncline (Erto syncline), is filled with the Eocene Erto Flysch and "decapitated" by a D2 thrust fault, providing the best map-scale example of D1-D2 crosscutting relationships. Due to the strong mechanical contrast between Jurassic carbonates and Tertiary flysch, in this syncline spectacular duplexes were developed during both D1 and D2.
In order to quantitatively characterize the complex interference pattern resulting from two orthogonal thrusting and folding events, we performed a dip-domain analysis that allowed categorizing the different fold limbs and reducing the uncertainty in the reconstruction of the fault network topology in map view. This enabled us to reconstruct a high-quality, low-uncertainty 3D structural and geological model, which unambiguously proves that D1 deformations with a top-to-WSW Dinaric transport direction propagate farther to the west than previously supposed in this part of the Southern Alps, predating top-to-S D2 Alpine deformations.

P-T-time-fluid evolution of the Theodul Gletscher Unit (Western Alps)

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The Theodul Gletscher Unit (TGU) outcrops within the Zermat Saas ophiolite in the Western Alps. The tectonic unit consists of an association of mica-schists, chloritoid-schists, garnet-schists and mafic boudins. The sequence reached eclogite facies metamorphism during Alpine orogeny (2.2 GPa and 580 °C; Weber & Bucher 2015). Recent mapping revealed that the TGU forms a flat lying syncline with an axial plane striking East-West.

U-Pb dating of zircons from the schists and the mafic boudins returns Permian ages from 260 to 280 Ma with variable REE patterns and are interpreted as detrital grains from multiple crustal source rocks. The metre-scale intercalation of mafic and felsic schists suggests sedimentation in a rifted passive margin associated to volcanic activity. Zircons found in the underlying gabbro are 167 Ma in age (U-Pb) and are associated to the opening of the Piemont-Ligurian ocean.

The bulk rock chemistry of the mafic rocks displays high variability in CaO (1.1-22.4 wt%), Na_2O (0.01-3.0 wt%) and K_2O (0.01-1.1 wt%). The composition of the schists is strongly depleted in CaO and enriched in NaO, Al_2O_3, TiO_2, FeO with respect to the Zermatt Saas ophiolite metasediments. These trends suggest a fluid-mediated exchange between mafic and felsic rocks during seafloor alteration.

A complex multi-stage metamorphic evolution is highlighted by quantitative mapping of garnet, which is present in every lithology. Thermodynamic modelling performed on garnet from the schists confirms the Alpine monometamorphic nature of the tectonic unit (peak at ~2.5 GPa and 550 °C). Moreover, rutile and graphite provide independent constraints on the metamorphic temperature conditions. Zr-in-rutile thermometry yields temperatures of 520–550 °C at 2.5 GPa. Geothermometry performed on graphite located either in the matrix or as inclusions in garnet gives a coherent peak metamorphic temperature of 540–580 °C.

In situ oxygen isotope analyses on garnet of the schists show a dramatic drop in $\delta^{18}O$ from ~12 ‰in the core to ~4 ‰in the rim. The significant variation in $\delta^{18}O$ is coherent with the chemical zoning in major elements and indicates open system fluid-rock interaction at high pressure, with input from mafic/ultramafic sources. In the mafic eclogites, the garnet $\delta^{18}O$ value is relatively homogeneous across the garnet crystals and has low values of 1–2 ‰, in line with deep sea floor alteration of the protolith prior to subduction. The combined data suggest that fluid liberated by the breakdown of lawsonite in the eclogites interacted with the adjacent schists, triggering complex dissolution and precipitation reactions.

In summary, the TGU is a volcanoclastic sequence, altered at the oceanic floor in the Jurassic and subducted to high-pressure conditions within the Zermatt-Saas ophiolites. The unit underwent significant metasomatism during the oceanic stage, and later in the subduction channel.

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Is the basin formation in the Pyrenees different from the Alps ?

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While several tectonic models are proposed to explain the formation of extensive basins and passive margins (simple shear, detachment, mantle exhumation ....), a single thermal model (McKenzie, 1978), as a kind of dogma, is used to understanding and modeling the formation and evolution of sedimentary basins. The study of the thermal evolution, coupled with other tectonic models, and its consequences have never been really studied in detail. Petrological changes, related to temperature evolution, modify rock density and then the subsidence history of the basin.

Recent studies of continental passive margins collectively describe a great variety of processes accounting for the extreme thinning of the continental crust. Among all the parameters that may act during crustal stretching, the thermal state of the system and the temporal evolution of the heat distribution during thinning appear of major importance.

Constrained by the new field data from the north Pyrenean basins about thermal evolution of early margin formation, we explore effect of different thermal evolution on petrological changes and their consequences on the geophysical signature of rifted zones associated to different thermal evolution and the consequences on the subsidence of the basins. We will also present numerical models quantifying mineralogical and physical changes inside the whole lithosphere during rifting processes. In the light of these models, we discuss the consequences of different thermal evolution on the subsidence processes as well as on gravimetric and seismic velocities signature of passive margins.

We are able to distinguish two types of margins according to their thermal evolution:

- An Alpine-type basin in which the temperature rise is 50 to 100 Ma older than the tectonic extension, leading to the "cold" opening of the ocean.
- A Pyrenean type basin in which temperature changes are synchronous with basin formation, leading to a crustal boudinage and to the formation of a “anomalous” geophysical layer at the OCT

Seismic imaging in the puzzle of overdeepened Alpine valleys

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Glacial erosion has formed overdeepened valleys and basins, spread over the entire Alpine realm. Subsequent to their erosion, glacial, lacustrine, and/or fluvial deposits have (partly) refilled these troughs. The International Continental Drilling Program (ICDP) funds the project "Drilling Overdeepened Alpine Valleys" to investigate the spatio-temporal evolution of past glaciations in the European Alps by the analysis of the sedimentary succession of overdeepened valleys.
Seismic imaging can can contribute to decipher this puzzle. High-resolution seismic reflection methods reveal the sedimentary succession and project 1-D borehole information spatially. Here, we reveal the erosional and sedimentation history of two Quaternary basin: The Tannwald Basin, Germany (TB; Burschil et al., 2018) and the Lienz Basin, Austria (LB; Burschil et al., 2019). The TB is bedded in Tertiary molasses in the Alpine foreland. Seismic imaging unravels the 240 m thick sedimentary succession, from bottom to top: basal till, allochthones molasses units, basin fines and till of the Dietmanns Fm. (Hosskirchian-Rissian stage), till sequences of the Illmensee Fm. (Rissian-Wurmian stage), and gravel/coarse sand. From that, we hypotheses plucking and deposition of large-scale molasse blocks during glacial erosion. The LB, surrounded by the High Tauern and the Gailtal Alps, is one of the deepest basins in the Eastern Alps (>600 m). Seismic imaging allows us to quantify a local overdeepening of 146 m as part of the Upper Drau Valley that shows >530 m overdeepening. A reverse slope of the basin base exceeds the estimated gradient of the ice slope during last glacial maximum (LGM) that lead to a freezing of subglacial meltwater. Consequently, we infer that glacial erosion has taken place pre-LGM. The sedimentary succession comprises from basin base to surface: basal till with slumping, lacustrine sediments, fluvial deposits of various facies, coarse clastics, and gravel/coarse sand. The overdeepened structure let us estimate a minimum paleo-water depth of 216 m at the beginning of the lacustrine sedimentation that fits well to 246 m of lacustrine deposits.
In conclusion, seismic imaging is a powerful tool to unravel details of the genesis of overdeepened valleys. We demonstrate the method at two diverse examples of overdeepened basins, one in the Alpine foreland and the other inner-Alpine.

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Inferring the drivers for crustal heating from the metamorphic rock record: modern and Archean examples

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Attainment of high mid-crustal temperatures is an important component of the evolution of many orogens and has significant consequences for the rheology of orogenic cores. Syn-orogenic partial melting and the generation of strong, dense residua also play essential roles in the long-term stabilization of continental roots and may have been critical to early Earth cratonization. Improved understanding of the processes that lead to elevated crustal temperatures is thus paramount for understanding both the evolution of modern tectonic plate boundaries and the mechanisms that led to the formation of stable cratons. Metamorphic duration is diagnostic of its thermal drivers and can be inferred with combined isotope geochronology and diffusion modeling. However, appropriately reading the metamorphic rock record can be difficult in cases that have possibly experienced multiple metamorphic events, with enigmatic evidence of polymetamorphism being recorded in many metamorphic belts.

Comparison of the metamorphic history of two Neoarchean terranes allows us to begin to characterize the diversity of tectonic style at a crucial period of Earth history, ~ 2.7–2.8 Ga. The Beartooth Mountains expose rocks of the Wyoming Craton that are dominated by an ~2.8 Ga calc-alkaline granitoid batholith which contains widespread, km-scale, granulite-grade meta-sedimentary roof pendants. The Pikwitonei Granulite Domain (PGD) consists of >15,000 $km^2$of high-grade metamorphic rocks in the NW Superior Province. Both terranes have previously been interpreted as reflecting cratonic margins undergoing metamorphism and magmatism at approximately 2.7 Ga. *P-T* paths from each domain appear to record clockwise evolution, reaching temperatures of ~800 and 950˚C, respectively, at ~5–8 kbar. However, metamorphic timescales are dramatically different in each terrane. Available data from diffusion modeling and isotopic constraints imply that granulite-grade conditions were achieved in the Beartooth rocks for < 2 Myrs. In contrast, U-Pb and Sm-Nd garnet data suggest maintenance of high-temperatures in the PGD for up to 100 Myrs. Zircon and monazite from some of the PGD's hottest rocks suggest growth pulses over durations far briefer than the overall regional-scale high temperature evolution, possibly implying temperature cycling over several tens of millions of years in which rapid and localized phases of > 800˚C metamorphism were superimposed on a much longer duration ~ 700˚C event. Taken together, the depths, temperatures and timescales inferred here imply contrasting processes of Archean crustal heating in the Beartooth and Pikwitonei settings.

Impact of convection in the mantle transition zone on long-term lithospheric deformation during the Alpine cycle

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The geodynamic history of the Western Alpine orogeny comprises periods of distinct phases of lithospheric deformation. Ultra-slow to slow spreading during ca. 60 Myrs formed the ca. 300-400 km wide Piemonte-Liguria basin. This basin was bounded by magma-poor, hyper-extended continental margins of the European and Adriatic plate and consisted mainly of exhumed and partially serpentinized sub-continental mantle. Subsequently, post-extension cooling took place for ca. 70 Myrs with insignificant tectonic activity. Then, convergence of the basin-margin system started at ca. 90 Ma causing the closure of the basin during subduction and the formation of an orogenic wedge during continent-continent collision.
Modelling the long-term geodynamic history (>100 Myrs) of orogens such as the Alps, including the pre-orogenic extension and cooling stages, remains challenging. For example, significant heat loss due to thermal diffusion over large time scales leads to unrealistic temperature and viscosity fields in the models. Modelling mantle convection in the transition zone below the thermal lithosphere-asthenosphere boundary (LAB) provides a mechanism to decrease the heat loss and stabilize the LAB in depth. Thermal effects of convection can be modelled by either (1) directly modelling small-scale mantle convection, or by (2) artificially scaling the thermal parameters of the sub-lithospheric mantle without modelling convection.
We perform 2D high resolution thermo-mechanical numerical simulations of more than 200 Myrs of lithospheric deformation. The models include the mantle transition zone down to a depth of 660 km to model the Western Alpine cycle including three subsequent deformation phases: (1) formation of a ca. 350 km wide basin of exhumed mantle bounded by two hyper-extended passive margins during a 60 Myrs rifting period. (2) Thermal relaxation of the margin system for 70 Myrs with no far-field tectonic activity. (3) Convergence of the passive margin system leading to subduction initiation, basin closure and orogenic wedge formation. We perform two types of simulations: (1) We resolve and model sub-lithospheric convection during lithospheric extension, cooling and convergence. (2) We scale the thermal conductivity of the sub-lithospheric mantle without modelling and resolving the convection. We discuss and quantify the general differences of the model results for the extension, cooling and subduction phase. We further quantify differences in effective viscosities in the models and their impact on the extension and subduction dynamics.

Elastic barometry on zircon inclusions in garnet megablasts from the Dora Maira Massif (Western Alps)

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In this study, we applied the elastic barometry method to several zircon inclusions from three garnet megablasts from the whiteschist lenses of the Brossasco-Isasca ultra high pressure (UHP) unit. By combining the Raman scattering with cathodoluminscence imaging and trace element analyses of exposed zircon grains, we have first established a protocol enabling to distinguish pristine zircon crystals from those partially or entirely metamict. Then, we have extended the analysis to buried inclusions with almost rounded or ellipsoidal shapes, using only Raman spectroscopy, to select those grains whose wavenumber variations are solely dependent on the strain acting on the inclusion. From the measured Raman peak position, we determined the strain state adopting the phonon Grueneisen tensor approach (Murri et al 2018).
Our results show that the selected buried zircon inclusions display a systematic decrease in the phonon frequencies moving from grains entrapped at the core toward those entrapped at the rim of the garnet host; consequently, the calculated residual pressure (P_{inc}) shows the same trend. Since no other host-inclusion system was available, we used pseudosection modelling and the Zr content in rutile inclusions to define a temperature range for garnet formation. Coupling these temperature estimates with the isomekes calculated from the residual pressure on zircon inclusions, we determined increasing entrapment pressure (P_{trap}) and temperature from core to mantle and rim of the garnet host. Our estimates are in agreement with previously published results for garnet growth on the prograde path, on the Brossasco-Isasca UHP unit (e.g. Chopin, 1984). This study shows that zircon elastic barometry is a promising new tool to constrain pressure in metamorphic minerals and opens the avenue to reconstruct detailed pressure-temperature-time paths.

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The Pennine Basal Thrust (Swiss Alps): a structural and geochronological study

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The Pennine Basal Thrust (PBT) is a major thrust of the Alpine orogeny that developed from late Eocene to Miocene during continental collision. Here we trace its evolution, by studying five samples, with indications for up to three microstructurally diachronous white-mica generations, which were investigated by laser in-situ and step-heating ^{40}Ar–^{39}Ar dating. From field relationships, four stages of deformation (D_1 to D_4) are distinguished in both the footwall (Helvetic Wildhorn Nappe) and hanging wall (Sion-Courmayeur zone; SCZ) of the Pennine Basal Thrust (PBT). Microfabric analysis shows that white mica was newly grown in three of the related foliations (S1 to S3) concomitant with (W)NW-directed shear. Three deformation-related crystallization ages can be distinguished: (1) D_1, characterized in the PBT hanging wall by an S_1 foliation defined by white mica + chloritoid, began at or before ~38.0 Ma; (2) D_2 formed a pervasive S_2 cleavage and synchronous white-mica rich veins dated at ~27 Ma; (3) D_3 produced an S_3 crenulation cleavage and chlorite + white-mica veins dated at ~23 Ma. Older ages of ~96 Ma (footwall) and ~115 Ma (hanging wall) are interpreted as minimum ages for the detrital component. Finally, discrete faulting produced fault gouge, with an illite K–Ar age of ~19 Ma. A simplified back-restored reconstruction provides a tectonic context for the dated structures. In this framework, D_1 occurred during middle to late Eocene tectonic accretion. Back-restoration along a cross-section through the area provides a regional tectonic context for the new ^{40}Ar–^{39}Ar and K–Ar data and places constraints on the beginning/end timing of specific events during Alpine continental collision. After late Eocene tectonic accretion, which we relate to D_1 in the hanging wall, top-to-NW shearing and localized shear on the PBT megathrust was probably slowed or interrupted by early Oligocene in-sequence development of the Ultrahelvetic Basal Thrust within the footwall. Renewed top-to-NW shearing on the PBT, assigned in our scheme to ongoing D_2, represents an Oligocene out-of-sequence reactivation of the megathrust. Subsequently, from ~23 to ~19 Ma, both plates (and the PBT itself) were affected by D_3 folding, associated with newly established in-sequence wedge propagation and antiformal stacking in the footwall. Younger brittle faulting along the PBT occurred from the early Miocene, constrained by ~19 Ma K–Ar ages on the fine fraction (<2µm) of authigenic illite from the clay fault gouge. This faulting developed at a time of ongoing convergence and orogen-parallel extension, during activity of the Rhône-Simplon fault system and possibly contemporaneous with scattered but regionally developed D_4 kink folds.

Dating of HP/HT Alpine metamorphism: petro-chronological and micro-structural study from the Cima di Gagnone (Cima Lunga unit, Central Alps)

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The Cima Lunga unit represents one of the most studied area in the Central Alps thanks to the occurrence of (ultra)high pressure and high temperature mineralogical assemblages developed during the Alpine phases. It consists of continental basement rocks (orthogneisses, paragneisses and metapelites) hosting (ultra-) mafic relicts of oceanic crust (eclogite, amphibolites and peridotites) which record pressure and temperature up to 2.5 GPa and 750 °C, respectively (e.g. Heinrich, 1982). This metamorphic peak is well constrained between 40 and 35 Ma (e.g. Gebauer, 1999).
The metamorphism of the surrounding gneiss complex is instead constrained at considerably lower conditions (up to 0.8 GPa and 660 °C; Grond et al., 1995). The temperature peak in the felsic rocks is dated at ca. 32 Ma (Gebauer, 1996), coeval with the Bergell emplacement. Our research consists in a petro-chronological and micro-structural study to refine the pressure-temperature-time-deformation evolution of the gneissic rocks enveloping the ultramafic boudins of the Cima di Gagnone.
The aim is to investigate if the deformation may significantly influence the pressure and temperature record within the rocks. We performed petrological (thermobarometry and thermodynamic modelling) and microstructural (SEM-EBSD) analyses to define the deformation and metamorphic patterns of samples collected close and far from the ultramafic inclusions. Our results indicate that some portions of the gneissic matrix preserve relicts of high-pressure and high-temperature metamorphism.
The resulting pressure-temperature paths are temporally constrained by U-(Th)-Pb dating of monazite and allanite, which provides ages estimations of the metamorphic evolution recorded by the gneisses. Preliminary data suggest a Late Eocene age for the high-temperature event, predating the regional Barrovian overprint.

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Sedimentary systems associated with the necking of continental crust during rifting: the example of the 'Grès Singuliers' around the Mont-Blanc massif (Western Alps)

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The Grès Singulier is a Liassic sandstone formation belonging to the Mont-Blanc autochthonous cover (External Crystalline Massif). The occurrence of punctual clastic deposits in a carbonated environment is striking (which explain the name 'Singuliers') and it raise questions concerning the detrital source(s), the depositional environment and the paleo-bathymetry.

This study is based on field work in the Mont-Blanc massif area, especially in the Col du Bonhomme, south of the Mont-Blanc massif. A multidisciplinary approach using sedimentology, stratigraphy, petrology and detrital zircon analysis was applied.

Diagnosis fault rocks (impregnated cataclasites and black gouges) belonging to an extensional detachment fault were observed on the top of the Mont-Blanc. The detachment fault is overlain by the autochthonous cover composed of pre -rift sediments Triassic to Hettangian in age. The Grès Singulier Fm. (Hettangian to Pliensbachian) is lying on the pre rift cover above an important erosional surface. It is composed of coarse-grained sediments with a calcite cement on the base and a phyllosilicate and quartz matrix in the rest of the formation. Petrological observations on the Grès Singulier fm. indicate a possible partial reworking of Liassic detachment, (as indicated by the presence of diagnostic pebbles of cataclasite and clasts of pseudotachylite).

The exhumed fault rocks were likely reworked by aerial/sub-aerial gravity flows in the basin and transported by shore-parallel tidal currents.

The deposition of the Grès Singulier fm. occurred simultaneously with localization of the extension and the major thinning (e.g. necking) of the crust/lithosphere resulting in the future European margin and subsequent Alpine Tethys ocean. The necking process corresponds to the localization of the deformation during rifting which is responsible for the thinning of the crust. It is known from numerical models that this phase is accompanied by important vertical movements. Previous studies showed that the European necking zone of the Alpine Tethys is preserved in the External Crystalline Massifs (Western Alps).

Based on our observations and previous studies, we therefore interpret the Grès Singulier as the sedimentary sequence recording necking of the European crust/lithosphere during Jurassic rifting. The necking phase manifested by the occurrence of a large extensional detachment fault that is responsible for the exhumation of basement, the formation of allochthonous blocks made of pre-rift sediments leading to the formation of a core complex type structure (Mont Blanc core complex) and formation of narrow, basins. The sediments facies suggest the existence of a general micro-tidal environment with tidal currents amplified in these narrow seaways that were strong enough to generate sediment transport. The tectono-sedimentary evolution of these environments was controlled by the dynamic exhumation and the related vertical and horizonal movements of the basement generating a complex syn-rift sedimentary sequence characterized by constant reworking and redeposition.

The study of the Grès Singulier fm. is important as it records the necking phase which is the transition from the stretching to the hyper-extension phase. It gives the opportunity to understand the sedimentary response due to the necking of the crust/lithosphere during rifting and to date the timing of necking, which is difficult at present-day margins due to the lack of well data.

Fossil oceanic core complexes in the Alps. New constraints from the Tethyan Aiguilles Rouges ophiolite (Val d'Hérens, Western Alps, Switzerland)

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The Aiguilles Rouges ophiolite (Val d'Hérens, Switzerland) exposes a large volume of remnants from the Alpine Tethys oceanic lithosphere, only weakly affected by Alpine metamorphism (greenschist facies conditions, Raman thermometry: 370-380°C) and associated polyphase deformation. Lithological sequences similar to present-day slow-spreading environments were observed, involving exhumed serpentinized and carbonated peridotites, gabbros, pillow basalts and tectono-sedimentary cover rocks. One remarkable feature is the presence of a kilometre-scale gabbroic complex, displaying preserved magmatic relics, textures and cross-cutting relationships between the host gabbro and intruding dolerites/albitites.
The whole rock major and trace elements compositions of mafic rocks are typical of N-MORB magmatism (Ce_N/Yb_N : 0.42-1.15). This is supported by in-situ isotopic signatures of magmatic zircons ($\varepsilon Hf_{176/177}$ = +13 ±1.1) and apatites ($\varepsilon Nd_{143/144}$ = +8.6 ±0.7), extracted from two gabbroic lithologies. These isotopic values are corrected to the age of magmatic emplacement. In-situ U-Pb dating of zircon was performed by laser ablation-ICP-MS, providing ages of 154.9 ±2.6 Ma and 155.5 ±2.8 Ma, among the youngest determined in the Alps.
Our results suggest that the former Aiguilles Rouges domain was characterized by magmatic activity and geometries comparable to present-day oceanic core complexes and similar to the Chenaillet –Queyras Tethyan opholites. Therefore, it may represent a more oceanward section of the Alpine Tethys compared to some ophiolite segments that were identified as ocean-continent transitions.

Structure and Deformation of the Central-Eastern Aar Massif

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The Aar massif in the Central Alps of Switzerland is a block of uplifted crystalline basement, which represents the largest External Crystalline Massif (ECM) of the Alpine orogen. Recent tectonic studies of structural and thermo- chronometric data have put new constraints on the deformation and exhumation history of the Aar massif. These data suggest exhumation of crystalline basement along steep vertical shear zones as well as along-strike differences in the growth of the massif, which are accommodated laterally by NW-SE trending strike slip faults. With additional information from previous seismic tomography studies, delamination of the lower European crust as a result of slab rollback was proposed as the main driver for the uplift of the Aar massif.
In this study, we compare the aforementioned tectonic models with tomographic images of the crust. We present our most recent 3D tomography model, which is based on high-quality local earthquake travel times of the past 22 years. More than 50,000 P and 25,000 S-wave arrival times allow the imaging of the upper crust for major parts of the Central-Western Alps with a spatial resolution of 10x10x4 km. We focus our comparison on the central-eastern part of the massif. In particular, we study the structure of its eastern termination, where the crystalline basement plunges towards east beneath the Helvetic nappes and thermo-chronometric data predicts the maximum exhumation rates from ca. 10 Ma to present.
We assess the neotectonic deformation of the Aar massif and its cover by newly derived high-precision earthquake relocations, focal mechanisms, and geodetic data. We provide high-resolution insights into the source region of the ML 4.6 Urnerboden earthquake of 2017, which is also located near the eastern termination of the massif, where the Helvetic nappes are immediately adjacent to the northernmost outcrops of the crystalline Aar massif. Our results document a rare but striking agreement in the seismicity pattern observed within the Aar crystalline massif near its basement-cover contact with faults outcropping at the earth's surface in the Helvetic nappes due to neotectonic activity along subvertically oriented strike slip faults. Such agreement suggests that the entire upper crustal section down to the uppermost portion of the eastern Aar massif presently deforms as a block, with the deformation in the sediments of the Helvetic nappes not being decoupled from deformation within the underlying parautochthonous wedge of the Aar crystalline massif. This implies a change from Helvetic nappes thrusting mode active during the Miocene towards neotectonic activity dominated by strike-slip mode in the studied region.

Tectonic significance of Variscan Barrovian metamorphism inside and outside the Alpine Front: the Orobic vs Maures basement

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The Variscan basement of Orobic Alps (Central Southalpine basement) comprises micaschists and gneisses, interlayered with metagranitoids, metabasics, marbles and quartzites. Early Palaeozoic ages are inferred for sedimentary protoliths (e.g. Gansser & Pantic 1988), whereas the metaintrusives mainly derive from Ordovician granitoids (e.g. Colombo et al. 1994; Bergomi 2004). In the Orobic basement, tectono-metamorphic units characterised by staurolite-bearing mineral assemblages are surrounded by units that fully developed their structural evolution under greenschist facies conditions (Spalla & Gosso 1999; Zanoni & Spalla 2018 and refs therein). St + Grt + Bt + Wm + Pl + Qtz ±Ky assemblages developed at metamorphic climax in metapelites and are locally predated by Cld-bearing parageneses. The ages proposed for the Barrovian peak range from 340 and 310 Ma (e.g.: Mottana et al. 1985; Diella et al. 1992; Bertotti et al. 1993; Siletto et al. 1993) and the metamorphic imprint is classically interpreted as due to the thermal relaxation consequent to the Variscan collision.

Similar rock assemblages and metamorphic parageneses characterises the western Maures basement, representing the external part of the southern French Variscan belt, where ages similar to those obtained in the Orobic basement are proposed for the St-bearing assemblages (330-320 Ma, Schneider et al., 2014). Both these portions of Variscan basement, at present located inside and outside the Alpine fronts, re-equilibrated under greenschist facies conditions during the late Variscan exhumation. The translation to shallower crustal levels is accompanied by a transition from Barrovian (intermediate P/T ratio) to Abukuma (low P/T ratio) metamorphic gradient.

The tectonic evolution and metamorphic history of the two basements are here discussed also on the basis of recent numerical simulations of a subduction-collision system. Numerical model highlights that the Barrovian imprint can also develops during subduction (Regorda et al. 2017) and not exclusively during continental collision (e.g. England & Thompson 1984; Gerbault et al. 2018).

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The origin of the Cimes-Blanches Nappe and the tectonic structure of the Penninic Alps

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The Cimes-Blanches Nappe is a sedimentary rock sequence ranging in age from Permian to Jurassic, originally deposited on continental crust from which it was detached during the Alpine orogeny. It is overlain by the Tsaté Nappe (Jurassic ophiolites and their sedimentary cover). Both were overprinted by Alpine blueschist- to greenschist-facies metamorphism. Below the Cimes-Blanches Nappe follows the eclogite-facies Zermatt-Saas Nappe, also including Jurassic ophiolites and, additionally, slivers of continental basement rocks. Two solutions have been proposed for the derivation of the Cimes Blanches sediments: From the Brianconnais (St. Bernard Nappe) by top-southeast-directed back-shearing, or from the Cervinia microcontinent (Dent-Blanche Nappe, Sesia Nappe) by top-northwest-directed pro-shearing. Structural work showed a predominance of top-northwest shearing, supporting an origin from Cervinia (Pleuger et al., 2007, Int. J. Earth Sci., 96, 229-252). A new sedimentological-stratigraphic study of the Cimes-Blanches Nappe (Passeri et al., 2018, Ital. J. Geosci, 137, 478-489) has augmented the evidence for a Cervinia derivation by demonstrating that the Cimes Blanches Nappe shows more analogies with the cover remnants of the Dent-Blanche Nappe than with the St. Bernard Nappe.
We reconstruct the tectonic evolution as follows: The Cervinia microcontinent was located between two basins of the Jurassic ocean, the Tsaté Basin to the Southeast (between Adria and Cervinia) and the Zermatt Basin to the Northwest (between Cervinia and the Brianconnais). In a first step of thin-skinned thrusting, the Tsaté ophiolites were thrust NW-ward over Cervinia, taking some of the Cervinia cover along (Cimes-Blanches Nappe) and emplacing it further northwest on the Zermatt Basin and even on the Brianconnais. In a second, thick-skinned thrusting step, the Dent-Blanche and Sesia basement units were thrust out-of-sequence, also towards northwest, over the Zermatt-Cimes-Blanches-Tsaté „sandwich“ and thus became the highest unit in the nappe pile.
The paleogeographic position of Cervinia is thus similar to the one of Alcapeca in the Western Mediterranean, between two basins of Alpine Tethys. Cervinia may just represent a northward extension of Alcapeca.

New structural, petrological and geochronological constraints from the Susa Shear Zone (Susa Valley, Western Alps)

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A multidisciplinary approach to the study of collisional orogenic belts can improve our knowledge of their geodynamic evolution and may suggest new tectonic models. In the Western Alps, nappes of different origin are stacked, having recorded different metamorphic peaks at different orogenic evolution stages. This study focuses on the meta-ophiolites of the Piedmont Zone outcropping in the mid-Susa Valley (Western Alps), where the relationships between different units are well exposed. The Piedmont Zone is conventionally subdivided in the Internal Piedmont Zone (IPZ) and the External Piedmont Zone (EPZ), which recorded metamorphic peak under eclogite-facies and blueschist-facies conditions, respectively. IPZ is a remnant of the Mesozoic Alpine Tethys and consists of meta-ophiolites with thin metasedimentary cover, whereas EPZ consists of minor meta-ophiolites and thick oceanic metasedimentary cover (i.e., the Schistes Lustrès). Both IPZ and EPZ were deformed throughout four regional deformation phases (D1 to D4), which developed different axial plane foliations (S1 to S4). These units are coupled through a first-order polyphasic shear zone, the Susa Shear Zone (SSZ). The SSZ consists of a thick mylonitic zone, wherein two distinct generations of kinematic indicators occur (ME1 and ME2), showing Top-to-E and Top-to-W shear sense, respectively. Each mylonitic event developed a mylonitic foliation (Sm1 and Sm2).

S1 and S2 foliations are almost perpendicular each other at the mesoscale, along D2-related fold hinges in both IPZ and EPZ. These foliations are mostly defined by iso-oriented white mica flakes. Microstructural features reflect the same geometrical relationships as at the mesoscale. S1 likely developed at HP conditions (Ep-eclogite vs. Lws-blueschist facies conditions for IPZ and EPZ, respectively), as suggested by the composition of white mica (i.e. phengite). By contrast, S2 developed at LP conditions (Ep-greenschist facies conditions in both IPZ and EPZ) and is defined by muscovite. White mica defining the mylonitic foliations records a continuous transition from the first to the second tectono-metamorphic event: Sm1 is mostly defined by phengite, while Sm2 is defined by muscovite. The relative chronology inferred from meso- and micro-structural observations suggests that Sm1 was syn- to post-S2, while Sm2 developed later, likely syn-D4.

A new set of radiometric ages have been obtained by *in situ* Ar/Ar dating on white mica, performed at Potsdam University. Different generations of white mica defining S1, S2 and Sm1 foliations in both the IPZ and EPZ and in the SSZ, have been dated. Two main groups of ages have been obtained: S1 foliation developed at ~46-41 Ma in both IPZ and EPZ, while S2 foliation developed at ~40-36 Ma in both the units. The Sm1 mylonitic foliation was nearly coeval with the S2 (~39-36 Ma).

White mica defining the Sm1 mylonitic foliation has higher Si contents compared to that grown coevally outside the shear zone. This feature might suggest different metamorphic conditions for the S2 and Sm1 foliations, with an “anomalous” P increase along the ME1-related shear zone, possibly indicating the development of an overpressure field. Further investigations are still ongoing and alternative hypothesis (e.g. effects of local compositional variations) are also plausible.

Elastic geothermobarometry on multiple inclusions in a single host

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The characterization of the pressure and temperature (P-T) histories of subducted rocks is of key importance to unravel geological processes at all scales. Conventional element-exchange geothermobarometers are challenged in ultra-high-pressure metamorphic terranes as the subduction temperatures may exceed their closure temperature and minerals may undergo re-equilibration along their path. Elastic geobarometry applied to host-inclusion systems is a complementary method to determine P and T conditions of metamorphism that does not rely upon chemical equilibrium. Recent development of elastic geobarometry (Angel et al. 2019; Campomenosi et al. 2018; Murri et al. 2018) allows us to retrieve entrapment pressures for host-inclusion pairs from the residual strains acting on the inclusion. Because only a single measurement, the inclusion strain, is made, only a line in PT space of possible entrapment conditions, the entrapment isomeke, can be determined. Thus, the entrapment pressure along an isomeke can only be determined if the entrapment temperature is known.
An alternative is to calculate entrapment conditions for two types of inclusions that are believed, from petrological evidence, to have been entrapped at the same time. In this study we performed micro-Raman measurements on quartz and zircon inclusions trapped in garnets from a garnet-kyanite gneiss and a quartz-garnet vein from the Fjørtoft UHP terrane, Norway. From the micro-Raman data, using the program stRAinMAN (Angel et al. 2019), we calculated the strains at room conditions (Murri et al., 2018) and thus the entrapment conditions. The intersection between the two sets of isomeke calculated on multiple quartz and zircon inclusions demonstrates that measuring different inclusion phases trapped inside a single host allows unique P-T conditions for the host rock to be determined.

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Interactions between foreland basin and collisional wedge in the Western Alps: new sedimentological, structural and thermochronological data.

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In this study, we present new sedimentological, structural and thermochronological data to constrain both the foreland and the wedge evolution in the Western Alps. There, the molasse basin strongly differs from the North Alpine Foreland Basin, it is much smaller and thinner (and possibly divided in sub-basins), which might be related to the wedge dynamics.
We focused our study at the transition between the North and Western Foreland Basin, in the Oligo-Miocene basins between Chambéry and Geneva with new stratigraphic logs and the interpretation of available seismic profiles. We derive new paleogeographic/paleoenvironnemental maps coupled with thermochronological data (Zircon Fission Track and He/U-Th-Sm on zircon of the External Crystalline Massifs and detrital rock samples) to define precisely the detrital sources. Sedimentary supply started progressively to increase since the Oligocene, with turbidites followed by deltaic then fluviatile deposits. In the western part of the Rumilly basin, the transition between Chattian and Aquitanian strata shows the evolution from fluviatile to lacustrine deposition.
Sedimentary sources did not change and only a slight sediment progradation took place during the Chattian-Aquitanian. During the Burdigalian, subsidence of the depocentre was controlled by the Gros Foug and Salève thrust folds. In Burdigalian sandstones, one sample show two major populations in detrital zircon fission-track data with an older signal attesting to continuous supply of the Rupelian - Chattian source (peak at ca. 120 Ma) and a more recent peak (at ca. 34 Ma). In the south, detrital zircon fission-track data from Oligocene sandstones show a peak ca. 35 Ma with a short lag-time pointing to rapid exhumation.
Sediment supply in the western Alpine basin continued over the Chattian to Burdigalian, documenting erosion of the upper plate and Ligurian ultramafic rocks. The stark contrast with the South-Western Alpine basin both in terms of geometry and sedimentary sources may be explained by differences incollisional shortening and exhumation rates or location of the paleo-drainage divide.

The Gaugen Complex in time (Kreuzeck Mountains, Austria)

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In the Eastern Alps only a few lithostratigraphic complexes exist, where the pre-Alpine history of Austroalpine basement units can be studied in detail. This arises from Cretaceous and Cenozoic deformation and metamorphism that variously overprinted most of these units and obscured pre-Alpine features.
One example is the Gaugen Complex forming parts of the Drauzug-Gurktal Nappe System in the Kreuzeck and Goldeck Mountains, south of the eastern Tauern Window. The most common lithology is paragneiss with transitions to micaschist. Additionally, minor amphibolite, orthogneiss and quartzite bodies also occur. The different types of orthogneiss are commonly peraluminous and show volcanic arc signatures. Their age is assumed to be Cambrian or Ordovician. Marble layers appear in the upper part of the Complex and suggest sedimentation at least until the Devonian based on Sr-isotopic ratios.
In the metapelites, locally staurolite and rarely kyanite occur in equilibrium with garnet, indicating amphibolite-facies conditions. A three point Sm-Nd isochron age on garnet yields a late Variscan age of 306 ±5 Ma (two garnet fractions and whole rock), which is interpreted as crystallization age close to the metamorphic peak.
The Gaugen Complex is divided by the E-W striking Lessnigbach Shear Zone. It initiated in Jurassic and/or Early Cretaceous times and was reactivated in the late Cretaceous with a north side up sense of shear. From both sides of the shear zone, bulk rock and mineral chemical analyses as well as equilibrium phase diagram calculations with the Theriak-Domino software package (NCKMnFMASHT system with excess SiO_2 and H_2O) were carried out on representative samples. South of the shear zone, the observed equilibrium assemblage Grt-Bt-Ms-Pl-Ilm together with the measured composition of garnet, biotite, plagioclase and muscovite indicates metamorphic conditions of approximately 570°C - 6.5 kbar. The observed equilibrium assemblage Grt-Ky-St-Bt-Ms-Pl-Ilm from the north of the shear zone corresponds to a narrow trivariant field around 640°C - 6.5 kbar, which is confirmed by the chemical compositions of garnet, biotite, plagioclase and muscovite.
Rb-Sr biotite ages are about 280 Ma to the south of the shear zone, whereas to the north of it an age of ~220 Ma were determined. These ages are interpreted to reflect late Variscan cooling below 300±50°C and a slight rejuvenation during the Eoalpine (Cretaceous) lower greenschist-facies overprint, which was more intense to the north of the shear zone.
The Gaugen Complex records different peak temperatures (~570°C in the southern block, ~640°C in the northern block), but similar peak pressure (~6.5 kbar) to both sides of the Lessnigbach Shear Zone. Furthermore, cooling ages in the northern block are younger than in the south. The distribution of the data can be explained by the late Cretaceous north side up sense of shear along the Lessnigbach Shear Zone.

Variations in the 3D temperature field in a fossil subduction zone resolved by RSCM thermometry (Tauern Window)

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Structural observations in the central Tauern Window reveal a crustal-scale sheath fold formed under high-pressure (HP) conditions (ca. 2 GPa). The fold is a composite structure that isoclinally folded the thrust of an oceanic nappe derived from Alpine Tethys onto a unit of the distal European continental margin, also affected by HP conditions. This structural assemblage is preserved between two younger domes at either end of the Tauern Window. The domes are associated with temperature-dominated Barrow-type metamorphism that overprints the HP-metamorphism partly preserved in the sheath fold.
Using Raman spectroscopy on carbonaceous material (RSCM) on 60 samples from this area, we were able to distinguish domains with the original, subduction-related peak temperature conditions from domains that were overprinted during later temperature-dominated (Barrovian) metamorphism. The distribution of RSCM-temperatures in the Barrovian domains indicate a decrease of peak temperature with increasing distance from the centers of the thermal domes, both in map view and cross section. This represents a geotherm where paleo-temperature increases downward, in line with previous studies using, e.g., oxygen isotope fractionation and calcite-dolomite equilibria. However, we observe the opposite temperature trend in the lower limb of the sheath fold, viz., tendentially an upward increase in paleo-temperature. We interpret this inverted temperature domain as the relic of a subduction-related temperature field. Towards the central part of the sheath fold's upper limb, measured temperatures increase to a maximum of ca. 520°C. Contours of equal peak-temperature are oriented roughly parallel to the nappe contacts and lithological layering in cross section. Further upsection in the hanging wall of the sheath fold, temperatures decrease to where they are indistinguishable from the peak temperatures of the overprinting Barrovian metamorphism. We propose the following hypothesis to explain the subduction-related peak-temperature pattern: The pattern reflects folding of a subduction-related temperature field. Possibly, sheath folding occurred during exhumation, after the equilibration at peak pressure and temperature conditions.

Change from rollback subduction to oblique collision at the junction of the Dinarides and Hellenides

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The Dinarides-Hellenides orogen in the Western Balkans is a Late Cretaceous-Paleogene thrust-and-fold belt in the upper plate of the active Adria-Europe plate margin. The mode of convergence changes along strike, from roll-back subduction in the southern, Hellenic segment to highly oblique continental collision in the northern, Dinaric segment. The junction of these segments is marked by a 20° bend in the orogen and by a rotational normal fault trending at high angles to the orogen, the Skhoder-Peja Normal Fault. At depth, a ~150 km long NE-dipping slab anomaly representing the downgoing Adriatic Plate beneath the Dinarides lengthens across this junction and along strike to the SE, reaching ~900 km at the apex of the Hellenic arc. This slab is interpreted to have retreated from NE to SW as indicated in lithosphere-scale cross sections by the offset between the present plate interface and the Late Cretaceous Sava suture.

Clockwise bending of the orogen began in Eo-Oligocene time, with accelerated rotation of the Hellenic segment since the middle Miocene. The Neogene component of bending is associated with an increase in shortening on a basal thrust running along the orogenic front, from only ~10 km north of the junction to at least 100 km south thereof. Higher in the nappe pile, bending is accommodated by orogen-parallel extension, clockwise block rotation and out-of-sequence thrusting. This Neogene thrusting is transferred to the Hellenic orogenic front via lateral ramps on dextral transfer zones.

The driver of Neogene tectonics has been enhanced rollback of the Hellenic segment of the Adriatic slab in the aftermath of Eo-Oligocene slab tearing beneath the Dinarides. The SW-retreating Hellenic slab segment induced clockwise bending of the southern Dinarides and northern Hellenides, including their Adriatic foreland, about a rotation pole in the vicinity of the Mid-Adriatic Ridge. This supports the idea that the Adriatic plate fragmented into two subplates (Adria s.str. and Apulia) and that the Apulian subplate, which is attached to the Ionian Sea and Nubia and is currently subducting beneath the Hellenic arc, has behaved non-rigidly. Future experiments invoking passive-array seismology may resolve the structures accommodating this behavior.

Quantification of strain rates in the tectonic transfer area of the Alps to the Rhone valley

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The center and borders of the Western Alps show significant recent deformations: radial extension combined with an important phenomenon of uplift in the center and transgressive deformations in borders. The region of the Rhone Valley and the alpine foreland that surround this area, have high societal challenges (demography, nuclear and chemical industry). As part of this internship, we want to see how the transfer of active tectonics is translated from the Western Alps to the Rhone Valley and the alpine foreland in terms of stresses and seismic deformations. The Rhone Valley region, however, remains poorly resolved in seismic datas (e.g. only few focal mechanisms). It is for this reason that we try to estimate deformation rates according to 3 different methods: by seismic moment summation (strain rates between 1E-13 and 1E-11 / yr) , by statistical integration of a Gutenberg-Richter distribution (strain rates between 1E-12 and 10E-9 / yr) or by combining the total energy obtained by the previous method and associating it with an average mechanism calculated from a stress inversion (same amount of deformation is obtained and we have an information on orientation and mode of this deformation). We finish by comparing our strain rates tensors with those obtained by geodesy: we have 10 times less deformation (geodesy: 1E-9 / yr calculated however on surfaces of approximately 50 x 50 km) and the same mode and deformation orientation for the Alpes-Rhone Valley area (strike slip deformations with NS shortening and EW extension). For the Durance we obtain transpression with shortening NE-SW (only shortening NW-SE for geodesy). Finally, for the southwest of the Rhone Valley, extensive NW-SE deformations are obtained while Geodesy shows transpression with NW-SE shortening.

Ages for high-pressure metamorphism in the Western Alps obtained by Lu-Hf garnet dating

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Different units, outcropping in the todays Western Alps underwent high-pressure metamorphism related to subduction and collision for about 40 Ma beginning in the late Cretaceous (Rubatto et al. 2001) and lasting until the Oligocene (Duchêne et al. 1997).
To understand the history and the mechanisms of subduction and collision it is important to know precisely the time when the different units reached high-pressure metamorphic conditions. Furthermore precise ages are needed to reconstruct the paleogeographic origin of the different units.
Lu-Hf garnet dating of eclogites has been proven to be a powerful tool for the dating of high-pressure metamorphism (Hauke et al. 2019; Weber et al. 2015; Miladinova et al. 2018). We will present new ages obtained by Lu-Hf garnet dating from samples of different nappes in the Western Alps. From the Monte Rosa–, Gran Paradiso– and Dora Maira– massifs, which we interpret to represent former European continental crust. From a sample from the Punta Nera representing the Zermatt-Saas ophiolite and from the Monte Emilius a continental sliver in the Zermatt-Saas nappe.

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Raider of the lost (island) arc: Reconstruction of volcanic activity at the transition from subduction to collision based on detrital amphibole and pyroxene from the Taveyannaz sandstone

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Despite the continuous subduction of oceanic crust of the Alpine Tethys from about 80 to 32 Ma there is little direct evidence for island arc volcanic activity in the Alps. Nevertheless, indirect evidence for calc-alkaline volcanism is present in baslatic and andesitic clasts in the Taveynnaz sandstone that belongs to the Oligocene flysch units. The age of volcanic activity has been constrained by Ar-Ar dating of amphibole to 32.5±0.2 Ma (Ruffini et al. 1997) and zircon U/Pb data (Lu et al., 2018). However, the geochemical characteristics of the volcanic activity and its significance for Alpine tectonics have remained poorly explored. We have investigated the major and trace element composition of detrital amphibole (amph) and clinopyroxene (cpx) from the Taveyannaz locality and from samples from Haute-Savoy. The volcanic detritus was deposited on the European continental foreland plate within a deep marine, flysch-type environment. The suite comprises an alternation of density current sand- and siltstone deposits with some mudstone interbeds. Amph and cpx in a single sample display large variations in Mg# (molar Mg/Mg+Fe) and thus derive from multiple sources rather than from a single eruption. The Fe-Mg site distribution in cpx by single crystal X-ray diffraction constrains high closure temperatures ranging from 950-1080°C and fast cooling rates of 10-60°C per hour, characteristic of fast quenching of magma in water. These observations together with the size and the rounded shape of volcanic pebbles provide evidence for submarine transport of volcanic material from multiple sources to the site of deposition. The trace element patterns of cpx and amph perfectly match the patterns of the same minerals from volcanic rocks from the Biella volcanic suite, indicating that the volcanoes were situated on the upper plate of the Piemonte-Liguria subduction. The composition of the parental magma can be reconstructed from the trace element contents of the most primitive cpx and amph applying published mineral-melt partition coefficients. The resulting trace element patterns are characteristic of typical arc lavas that are generated by fluid fluxed melting of a mantle wedge above subducted oceanic crust. The new data provide insights into Alpine tectonics at the transition from subduction to collision. The volcanic activity is caused by oceanic crust subduction and extruded on the distal margin of the Southern continent. The quenched and eroded volcanic material was transported first to the NW to Haute Savoy and then to the NE to Taveyannaz for a distance of at least 100 km and was deposited in the European foreland basin, i.e. on top of the European continental plate. Therefore, docking of Europe and Adria must have occurred at 32.5 Ma. Interestingly, no water divide was yet present at this time, as marine channels must have existed between the source region of the volcanic products on the Adriatic plate and the deposition on the European plate. This suggests that the pronounced relief of the Alps developed shortly after, during the onset of collision between Adria and Europe.

External Crystalline Massifs: Geodynamic Witnesses of Late-stage Alpine Collision

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The occurrence and arcuate arrangement of the External Crystalline Massivs (EMC) as witnesses of the inverted remnants of the former only weakly extended European Passive Continental Margin in the Alpine mountain chain is unique in light of collisional orogens. In this presentation, we will discuss the structural and geodynamic evolution of the following major ECMs of the Central and Western Alps: (1) Aar Massif; (2) Mont Blanc / Aiguilles Rouges Massifs, and (3) Belledonne / Grandes Rousses / Oisans Massifs. Starting in the Aar Massif, the well-known general thrust (horizontal) tectonics of Helvetic- and Lepontine units (>22 Ma) is followed Aar Massif internally by a completely contrasting deformation style, namely reverse faulting-dominated vertical tectonics (22-13 Ma). In a late stage of collision, again a change to horizontal tectonics in a transpressive regime occurs (<13-12 Ma), which is manifest by thrusting in the northern part of the Aar Massif while dextral strike-slip dominates in the south. Along strike of the Alpine chain towards the west, the Mont Blanc Massif shows many similarities to the Central-Northern Aar Massif (strike-slip tectonics, steep shear zones, exhumation history, shortening) also pointing to a strong component of vertical tectonics. Few differences mainly reside in the fact that a long thermal peak is recorded in the Mont Blanc massif, as well as in other massifs further South. In contrast, to S-Aar and Mont Blanc Massif, the reduced shortening of the N-Aar /Aiguilles Rouges / Belledonne Massifs allow to unravel crustal shortening above thrust-ramps including classical thick-skinned fold-and-thrust belt deformation. These fundamental spatial and temporal tectonic switches during the evolution ECMs will be addressed by treating the following aspects:

- The 3D paleogeographic shape of the necking zone of the former European Passive Margin with its bulges and embayments.
- The resistive response (kinematics, PTt) of the relative low density European continental crust, with its complex geometry, to be dragged into the subduction zone.
- The rheological consequences and resulting uplift structures.

These points will be critically discussed for different geodynamic scenarios and driving forces for the exhumation of the ECMs, incorporating lithospheric forces and surface erosion processes.

Geophysics for Alpine geology: project AlpArray and beyond

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The Alps and Alpine orogeny have been studied for numerous decades by geologists and geophysicists, yet there are a number of challenges to overcome and knowledge gaps to fill. The first stems from the high level of spatial complexity along and across the Alpine arc, which requires fully 3D analyses in both imaging and modelling. The second stems from the gap in the scales between the majority of geological and geophysical investigations. A good example is the limited knowledge of the mid- and lower crust between well-mapped surface geology and well-known Moho depth. A third factor is sub-optimal information exchange between research communities. A major step in improving from the situation depicted above is initiated with the AlpArray project, but clearly, further and continued efforts are required.

AlpArray is a multi-national initiative to advance our understanding of orogeny and its relationship to mantle dynamics, plate reorganizations, surface processes and seismic hazard in the Alps-Apennines-Carpathians-Dinarides orogenic system. It's main effort so far was the deployment of a high-end seismological array, which allows high-resolution geophysical imaging of 3D structure and physical properties of the lithosphere and of the upper mantle. I will present the characteristics of the AlpArray Seismic Network, and also of other field experiments. First results and ongoing work will be summarized, including a 3D tomographic result of the entire Alps, and a high-resolution profile across the Eastern Alps. I will conclude on an outlook of what AlpArray will and will not be able to provide to the geological community.

In future phases of AlpArray and in the frame of other forthcoming projects, further efforts are needed, especially to integrate a wider range of observables, to make bridges across the scales, and for more efficient interaction between communities. The initiative of scientific deep drilling in the Ivrea-Verbano Zone is prime example. In general, a tighter collaboration is encouraged using geophysical inputs in geological undertakings. Such works should aim at linking research domains like tectonics and structural geology, seismology, petrology, gravimetry and electro-magnetic methods, geochemistry, geodesy, laboratory experiments, analogue and numerical modelling, surface processes, and –even –planetology.

Geodynamic setting of rocks above and below the Eo-Alpine extrusion wedge (Innsbruck Quartzphyllite Zone, Eastern Alps, Austria)

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In the Austroalpine units of the Eastern Alps, low-grade metapelitic rocks occur structurally above and below the high-metamorphic grade rocks of the Eo-Alpine extrusion wedge (Koralpe-Wölz Nappe System). Information about the P-T-t-D histories of the units above and below the extrusion wedge are currently limited despite their great importance to constrain the geodynamic setting for the Late Cretaceous exhumation of the high-pressure rocks. In this work we investigate the 'Innsbruck Quartzphyllite Zone' north of the Tauern Window, which consists of low-grade metasedimentary sequences. Recent structural mapping and new petrological and geochronological data showed that the Innsbruck Quartzphyllite Zone consists of several tectonic Austroalpine units that are located above and below the Eo-Alpine extrusion wedge: The lowermost Königsleiten Nappe belongs to the Silvretta-Seckau Nappe System (structurally below the Eo-Alpine extrusion wedge), the Windau Nappe and the Uttendorf Nappe both belong to the Tirolic-Noric Nappe System (structurally above the Eo-Alpine extrusion wedge).

Chloritoid-bearing phyllites from the Königsleiten Nappe exhibit a pronounced compositional layering, which is interpreted as an inherited sedimentary compositional heterogeneity, arguing for a simple deformation history. The mineral assemblage interpreted to be stable at the metamorphic peak comprises chloritoid, chlorite, muscovite, paragonite, quartz, ilmenite and allanite. Samples from the Windau Nappe show a polyphase deformation history, indicated by veins concordant to the main foliation that contain intrafolial folds. The assemblage in the phyllitic host rock is characterized by chloritoid, muscovite, quartz, rutile and subordinate Mg-siderite whereas veins contain coarse grained quartz, muscovite, Mg-siderite, dolomite and chlorite. Kyanite is found at the vein-host rock interface, commonly partially replaced by muscovite and kaolinite. Layers at the host rock-vein contact are typically enriched in accessory minerals that comprise rutile, monazite, apatite, xenotime and zircon. Compositional zoning of these phases indicates extensive dissolution and precipitation, probably related to vein formation. Samples from the Uttendorf Nappe comprise chloritic micaschist with several mm-sized chloritoid porphyroblasts. Depending on the bulk chemistry, either rutile or ilmenite is interpreted to be part of the equilibrium assemblage, indicating peak metamorphic conditions close to the rutile to ilmenite transition. Additionally, apatite and allanite commonly overgrown by an epidote rim were found.

Preliminary results from SEM imaging and EMP analyses combined with thermodynamic forward modelling indicate peak conditions of ~470°C and ~7 kbar for the Königsleiten Nappe and slightly lower P-T conditions for the Windau Nappe. Similar conditions are inferred for the Uttendorf Nappe from the rutile to ilmenite transition at ~450°C. We present new results from thermodynamic modelling with an extended model compositional space to account for REE-bearing phases (allanite, monazite, xenotime and apatite) which are suitable targets for U-Th-Pb in-situ dating using laser-ablation ICP-MS. Identifying prograde and retrograde reactions involving these minerals allows a better link of P-T and age data and thus helps resolving the temporal variation of the Cretaceous metamorphic evolution in the different nappes. Our new P-T-t-D data from units structurally above and below the extrusion wedge help to better characterize the overall geodynamics settings of the Eo-Alpine exhumation of high-grade rocks in the Eastern Alps.

Multiple fluid compositions preserved in an eclogite-facies apatite vein (Monviso Ophiolite, Western Alps)

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The Monviso Ophiolite (2.6 GPa, 550 ºC) has been the subject of a number of studies investigating fluid transport along shear zones and vein systems at eclogite-facies. Here we report an apatite vein found cross-cutting a typical eclogite-facies assemblage of garnet+omphacite+rutile+apatite±lawsonite pseudomorphs. The vein is made up of apatite with acicular omphacite inclusions and is bounded by a complex and layered alteration selvage. From vein to host, the alteration selvage varies from: 1) nearly monomineralic coarse omphacite with accessory neoformed garnet; 2) garnet+omphacite+rutile with fine-grained omphacite, atoll garnets and variable modal abundances; 3) undulose garnetite layer marking the transition from selvage to host-rock. Vein apatite is dominated by the hydroxyl-apatite endmember, instead of the fluor-apatite typical of high-pressure metamorphic rocks worldwide, suggesting the fluid from which the vein formed was F-poor. Fluoride-bearing fluids can increase the solubility of Ti by two orders of magnitude, so this F-poor apatite is unexpected given the mobility of Ti observed throughout the Monviso Ophiolite. No typical vein growth textures (e.g. epi-, syn- or anti-taxial mineral fibers, chemical zoning parallel to the vein wall) are observed, instead the apatite forms rounded subgrains and pinches and swells along its length. The only systematic chemical zoning in the vein is subtle variations in Sr along and across the vein, complemented by an inverse variation in HREE content suggesting two fluid compositions were transported by this vein. This dichotomy in apatite composition is also reflected in the selvage mineral compositions. Strontium concentration in omphacite generally decreases from host rock through the selvage with vein inclusions showing the highest concentrations, consistent with Sr loss to a fluid during selvage formation. In selvage layers 2 and 3, garnet is generally more HREE-enriched relative to the host rock suggesting that the HREE-bearing fluid was externally sourced and resulted in net HREE addition to the selvage. Selvage layers 1 and 2 also preserved some of the most HREE-poor garnet, possibly grown in response to the HREE-poor Sr-bearing fluid. Bimodal vein apatite compositions require the presence of two distinct externally-derived fluids transported by the vein, precipitating Sr-rich apatite and HREE-rich apatite. Loss of Sr from the selvage omphacite and the variable HREE content of selvage garnet and interpreted to result from interaction with these two distinct fluid compositions. The loss of Sr from the selvage is likely the result lawsonite or phosphate breakdown since these minerals are largely absent from the selvage. This apatite vein offers an opportunity to further characterize the spatial, temporal and chemical characteristics of fluid transport at eclogite-facies.

Oligocene/Miocene sediments from the Austrian Molasse did not reflect a large-scale surface response to slab break-off: results from detrital apatite fission track analysis

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The reconstruction of Earth-surface response to changes in geometry of the subduction zone on million-year time scales and the propagation of these tectonic signals into the sedimentary record is a matter of ongoing debate. A key area for investigating this topic is the Eastern Alps, where teleseismic tomographic images suggest present-day northward subduction of the Adriatic plate. The opposite subduction direction prevails beneath the Central Alps. The Upper Austrian Northern Alpine Foreland Basin (NAFB) offers an excellent opportunity to investigate the potential surface response of the Central and Eastern Alps to the proposed slab polarity switch at ~20 Ma during the Oligocene and Miocene, as this part of the basin formed the transfer zone for Alpine detritus.

During deposition of the deep-marine sediments of the Zupfing Formation (29.6–26.8 Ma), Lower (LPF) and Upper (UPF) Puchkirchen Formation (26.8–19.6 Ma), and the lower Hall Formation (19.6–18.1 Ma), sediment routing in the basin was largely controlled by a submarine channel system along the basin axis. The channel separated the basin into a wide, gently-sloping northern basin margin and a steep, tectonically active southern slope. Channel sedimentation terminated during deposition of the early Hall Formation at 19.0 Ma, concomitant with a sea-level highstand. Subsequently, northward prograding clinoforms filled up the basin.

In this study, we present 706 new detrital apatite fission track (AFT) single grain ages from Oligocene and Miocene sedimentary archives, represented by 22 drill cores and one surface outcrop. Basin stratigraphy was recently updated and, hence, the depositional ages of the strata are well known.

The AFT ages from the Puchkirchen Group show three distinct age populations: Cretaceous, Eocene, and Oligocene. The proportions of these populations change from dominantly Eocene ages (~60%) in the LPF to dominantly Oligocene ages (~50%) in the UPF. AFT ages from the Hall Formation are dominated (~75%) by Eocene ages; Oligocene ages are rare.

The new AFT ages suggest that parts of the Central and Eastern Alps (Lepontine Dome, Tauern Window) experienced an Oligocene exhumation event whereas other parts were relatively unaffected by this event and supplied Eocene and Cretaceous AFT ages (e.g. Silvretta or Ötztal nappe complex). The increase in young, Oligocene ages from the LPF to the UPF is either related to the acceleration of exhumation or a more efficient transport from the source areas to the Austrian NAFB. The dominance of Eocene ages in the Hall Formation and the increase in lag time reflect the uplift and redeposition of material from the Augenstein Formation in the south.

Our data contradicts the idea of a large-scale surface response to a tearing or break-off event underneath the Eastern Alps in late Oligocene/early Miocene times. The presence and partial dominance of Eocene and Cretaceous AFT ages suggest that large parts of the Central and Eastern Alps experienced slow and steady erosion during this time.

New age constraints on the tectonic evolution of the Adria/Piemont-Liguria ocean-continent transition in the Internal Western Alps

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The Internal Western Alps represent a stack of nappes that assembled during the Late Cretaceous - Paleogene Alpine orogeny. For some units the timing of high-pressure metamorphism and subsequent exhumation and retrogression is relatively well-constrained whereas for other units such information is still missing.

The Dent Blanche Basal Thrust in the Western Alps of Switzerland and Italy represents a fossil subduction interface that was active during Paleogene subduction and accretion of Adriatic continental margin units and Piemont-Ligurian oceanic lithosphere. In the western Valtournenche of Italy, greenschist- to blueschist-facies metasediments are exposed along this boundary zone between continental rocks of the Dent Blanche nappe in the hanging wall and dominantly oceanic rocks of the Combin zone in the footwall.

In-situ LA-ICP-MS U-Pb geochronology on various minerals (garnet, serpentine, calcite) is used to constrain the history of the metasediments and adjacent continental and oceanic units. Our preliminary results suggest a complex tectonometamorphic evolution of these units from Jurassic rifting over Paleogene subduction and high-pressure metamorphism to subsequent exhumation, greenschist-facies retrogression and late (sub)recent brittle deformation.

Control of mechanical heterogeneities on nappe detachment, transport and stacking in the Helvetic Nappe System

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Nappe systems are typical of many orogenic belts. A well-known example is the Helvetic nappe system in the Swiss Alps, which consist of sedimentary units that have been sheared and thrusted over the crystalline basement of the European passive margin during the Alpine orogeny. These sedimentary units form, for example, the parautochtonous Morcles nappe of the infrahelvetic complex, which is situated below the Helvetic Wildhorn super-nappe.
Although nappes were recognized a century ago and have been studied since then, the mechanisms responsible for nappe generation and nappe stacking are still debated. We present 2D high-resolution thermo-mechanical numerical simulations of the shearing of basement-cover system with half-graben representing the upper crust of the European passive margin. The scope of the numerical simulations is to evaluate the impact of the (1) geometry of the basement-cover interface, (2) presence of mechanical layering resembling the alternation of shale-rich and carbonate-rich sedimentary units. We are identifying the controlling mechanisms of the formation of the basal detachment zone. The final aim of the simulations is to reconstruct the overthrusting of the Helvetic nappes over the nappes of the Infra-Helvetic complex.

The pre-Mesozoic tectonic contact of the Schneeberg Complex and the pre-Permian sediments in the southeastern Ötztal Nappe (Austroalpine, Italy)

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In its southeastern part the Ötztal Nappe comprises the Ötztal Basement s. str., the Schneeberg Complex, the Laas Series and the Texel Complex. The latter is known as the western end of the Eoalpine High-Pressure Belt, for which several subduction and exhumation models exist. For assessing these models, it is essential to clarify the relationships inside the Ötztal Nappe.

Systematic electron-microprobe garnet mapping allows discrimination between different metamorphic histories in the southeastern Ötztal Nappe by zonation patterns. Alpine garnet growth is reported in all units. Variscan high-grade metamorphism is documented by inherited cores of two-phase garnets. While the internal parts of the Schneeberg Complex show only single-phase garnets, the Ötztal Basement s. str., the Laas Series and the Texel Complex show two-phase garnets. The Schneeberg Complex can be divided into the single-phase Schneeberg synforms and the two-phase Schneeberg frame zone (Rahmenzone). The tectonic contact between the Schneeberg synclines and the other units is therefore of pre-Alpine origin (Fig. 1). Garnet zonation does not indicate an Alpine contact between the Texel Complex and the Ötztal Basement s. str. This challenges models where the Texel Complex and the Ötztal s. str. represent the footwall and hanging wall of an exhumation-related normal fault (Sölva et al. 2005) or two different nappe systems (Schmid et al. 2004).

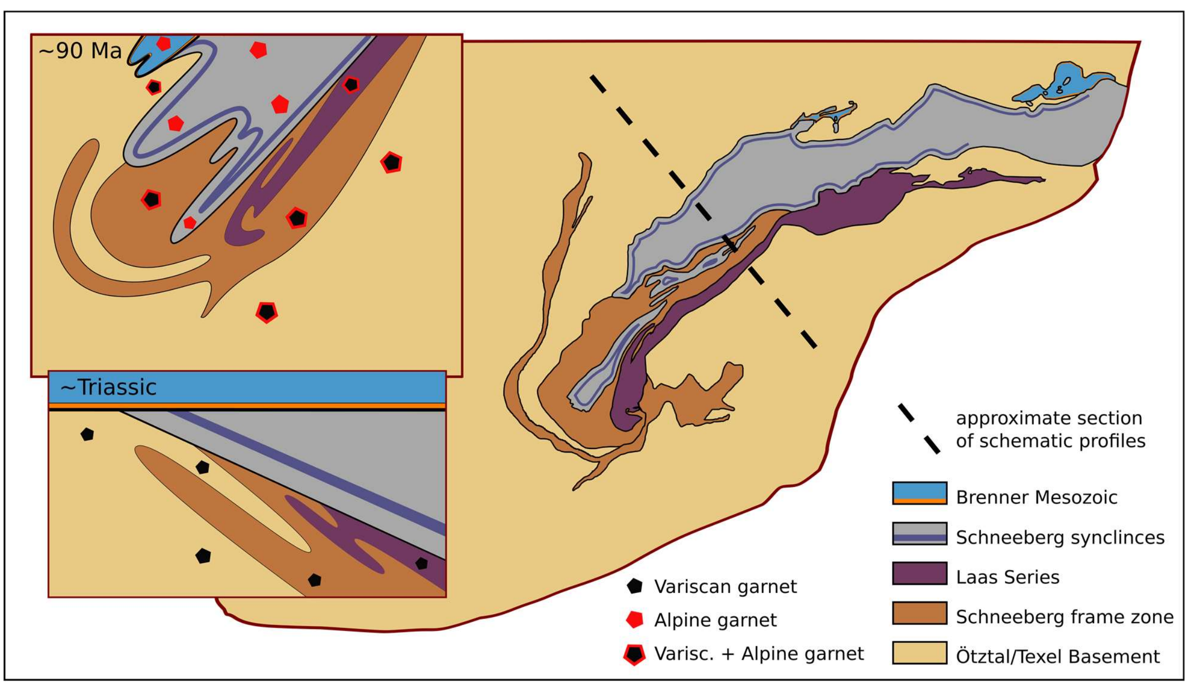

Fig. 1: Map of the southeastern Ötztal Nappe (after Mauracher 1980) with schematic profiles.

To test if the remaining contacts are of sedimentary nature, we used detrital zircon U-Pb dating by laser ablation ICPMS. Previous U-Pb dating of magmatic zircons of granitic intrusions in the southeastern Ötztal Nappe yielded Ordovician (450 –470 Ma) formation ages. Our set of detrital zircon ages indicates that the Austroalpine basement containing Ordovician magmatites is the source area of the metasediments of the Schneeberg Complex and the Laas Series. We suggest that the Schneeberg and Laas series represent the post-Ordovician, pre-Permian sedimentary cover of the Ötztal/Texel basement. In contrast to the Laas Series and the other units, the rocks presently found in the Schneeberg synclines belonged to a higher structural level of the Variscan orogeny, unaffected by Variscan garnet-grade metamorphism. Therefore, the basal contact of these Schneeberg rocks probably represents a Permian extensional fault or shear zone.

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The influence area of the Vals-Scaradra Shear Zone at the front of the Adula Nappe (Central Alps, Switzerland): Quartz textures and microstructures related to exhumation of subducted continental crust.

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The Adula Nappe is the structurally highest of the Lepontine Nappes in Central Switzerland and represents the distal part of the European margin, which was subducted and subsequently exhumed to upper crust levels. In contrast to over- and underlying units, the Adula Nappe experienced up to ultra-high-pressure conditions. To the north, the Adula Nappe ends in a lobe surrounded by Mesozoic metasediments. This frontal boundary of the nappe represents a discontinuity in metamorphic conditions, between higher T in the Adula Nappe and lower T outside. A shear zone with steeply dipping foliation and shallowly-plunging, WSW-ENE oriented, i.e. orogen-parallel stretching lineation overprinted the northernmost part of the Adula Nappe and the adjacent Mesozoic metasediments (Vals-Scaradra Shear Zone). It formed during the local Leis deformation phase. The Vals-Scaradra Shear Zone (VSSZ) is remarkable in that it exhibits a reversal of shear sense along strike; from sinistral in the west to dextral in the east. Quartz textures also vary along strike indicating sinistral shearing with a component of coaxial (flattening) strain in the west. In the east strong, single c-axis maxima point to dextral shearing with only minor flattening. A texture from the middle part of the shear zone is symmetric and indicates coaxial flattening.

The southern border of the VSSZ is already well mapped. The actually presented field observations as well as the crystallographic preferred orientations of oriented quartz samples from the surrounding metasediments (Grava Nappe, Piz Terri-Lunchania Zone, Valser Mélanges):

- confirm that the VSSZ also affect the sediments outside of the Adula Nappe and help to define the northern range of its influence in addition to it.
- reveal the kinematics and deformation conditions in the northern part of the VSSZ and in the following help to correlate different deformation phases in front of the Adula Nappe.

These relations reflect complex flow within and outside of the Adula Nappe during a late stage of its exhumation. These structures indicate that the Adula basement protruded upward and northward into the surrounding metasediments, spread laterally, and expelled the metasediments in front towards west and east. We think that VSSZ is an important piece of the Adula “puzzle” and may help to better understand its tectonic evolution, especially its final exhumation to the upper-crustal level.

How wide was the Liguro-Piemont Ocean?

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We present an updated kinematic reconstruction of the tectonic plates (Adria, Iberia, Europe, Africa) and micro-continental blocks (Corsica-Sardinia, Briançonnais, AlCaPa, Tisza, Dacia) involved in the Alpine Orogeny since 200 Ma. Our model is based on a compilation of geological and geophysical data and published reconstructions of the Mediterranean-Alpine area. The novelty is that our model is incorporated into a global Mesozoic-Cenozoic deforming plate motion model, constructed using the GPlates software (www.gplates.org) that includes the progressive extension of all continental margins since the initiation of rifting within Pangea, major failed continental rifts, the progressive compressional deformation along collision zones, and seafloor-spreading age grids of the ocean floor. The new version of GPlates (2.1) allows quantitative analyses of continental deformation during rifting and orogenesis (e.g. evolution of crustal thickness through time, stretching/shortening factor, strain rate).

The motions of Europe, Africa and Iberia are constrained in the global plate motion model by reconstructing continental rifting and spreading in the Atlantic Ocean. The motion of Adria is well-constrained back to 20 Ma by geological and geophysical data from surrounding orogens (Alps, Apennines, Dinarides) and basins (Liguro-Provencal Basin and Sicily Channel Rift Zone). However, uncertainties increase further back in time. Our main assumption is that the Ionian Basin is oceanic and opened in Triassic time and that, therefore, no significant extension or convergence has occurred between Adria and Africa since 200 Ma. For motion of the AlCaPa-Tisza-Dacia units, we use published tectonic restorations of the Alpine-Carpathian-Dinaridic system. We use tectonic reconstructions of the opening of the Liguro-Provencal Basin and of the Provence fold-and-thrust belt to constrain the motion of Corsica-Sardinia relative to Europe since 83.5 Ma. We then test different scenarios depending on if Corsica-Sardinia was part of the Iberian or the European plate between 200 Ma and 83.5 Ma. We discuss the implications of these different scenarios on 1) the pre-breakup position (200 Ma) of the Adriatic plate and its possible subdivision into two plates, and 2) the size of the Liguro-Piemont Ocean (or Alpine Tethys). Our model shows that the Liguro-Piemont Ocean must have been a narrow basin of maximum ca. 350 km width in a NW-SE direction in the Alpine area that opened between ca. 170 and 130 Ma, which implies ultra-slow full spreading rate of less than 10 mm/yr. This raises the question of the nature of the crust of the Liguro-Piemont Ocean and its margin (proto-ocean, hyper-extended continental crust), which is crucial to better understand subduction processes during the Alpine Orogeny.

Consistent Earthquake Catalog for Past 36 Years and High Resolution Imaging of Seismogenic Fault Zones in the Valais (Switzerland)

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Valais (southwest Switzerland) is the seismically most active region in the country. The seismicity north of the Rhone-Simplon line (RSL), which is the tectonic boundary between the Penninic realm in the south and the Aar massif and the Helvetic nappes in the North, concentrates in a narrow but 20km long E-W striking zone. The correlation of this zone of shallow seismicity with the proposed fault system and the geologically mapped local faults is still not well understood. In addition, it is sub-parallel to the RSL but with an apparent offset of 5-10km to the north. While RSL is characterized by dextral deformation that continued at least until 3Ma, it raises the question where current crustal deformation localized.
The instrumental seismic catalog well covers the last 36 years yet it is based on a station network that evolved through time. A station network configuration changing over time may not only introduce systematic errors in hypocenter locations and magnitude estimates but also causes varying location quality. As a result, such processing artifacts in the seismic catalog overlap with natural characteristics of seismicity and this severely limits analysis of long term spatial-temporal behavior and resolving fault geometries in high-resolution. To overcome these limitations, we establish a complete and highly-consistent earthquake catalog with known location accuracy by relocating all reported events for the last 36 years with the minimum 1-D model approach for the Valais region. The velocity models and absolutely well-located hypocenters are then used as initial values for a regional relative relocation procedure based on waveform cross-correlation to resolve the fine-structure of seismicity.
The results obtained from the new catalog show, while there are more seismicity clusters in recent 20 years, the seismicity pattern does not change significantly over time considering epicenter and depth distribution. This correlates with the smaller magnitude of completeness in modern era (2.2) than early (2.6). The highest-quality events with <1km epicenter and <2km depth uncertainty document a series of (En-echelon) fault segments north of the RSL. This finding correlates with changes in focal mechanisms at different section of the elongated zone of seismicity. We also found the vast majority of the events are shallower than 10km. Regarding the top of the crystalline basement resolved by NFP-20 refraction profile(2-5 km), this suggests only top part of the basement is involved in the current deformation process. The seismicity south of RSL, in contrast, exhibits a more wide-spread distribution of the event cluster and general we observe different focal mechanisms than N of the RSL. Nevertheless, the focal depth distribution is surprisingly consistent N and S of RSL. This indicates the main driving mechanism for the seismic activity in the Valais is not locally correlated with a specific tectonic unit, Helvetic nappes in the N versus Penninic nappes in the S.

The Plankogel complex within the Austroalpine nappe complex of Eastern Alps: a Paleotethyan suture?

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The pre-Alpine Austroalpine amphibolite-grade metamorphic basement of Eastern Alps contains a number of ophiolitic sutures, which are poorly constrained in age. All of them have been considered to have formed not later than Variscan plate collision during the Carboniferous. Major portions of this basement are then overprinted by Permian rift processes, which also include low-pressure rift metamorphism. As a result, the location of a Paleotethyan suture has not been considered to extend into the Alps.

Here we report preliminary results of an extensive U-Pb zircon dating and geochemical analyses on the Plankogel complex in Eastern Alps (Saualpe and Koralpe), which was considered to represent part of the pre-Alpine basement. The Plankogel complex is composed of coarse-grained garnet-micaschist as a matrix and plagioclase-rich biotite schist, within which hectometer-sized lenses of marble, manganese-rich spessartine-quartzite, amphibolite and ultramafic rocks occur. The marble was the host of a manganese-rich iron mineralization mined until ca. four decades ago. The amphibolites have a N-MOR-basalt geochemical signature. The manganese-rich quartzites were explained as siliceous deep-sea sediments. No protolith age were known up to now.

Metasedimentary rocks like the garnet-biotite-micaschist show a large population of Pre-Permian, partly euhedral zircons implying an age of the sedimentary precursor rocks not older than Permian. The manganese quartzites show a large Permian to Early Triassic volcanic component (244±6 –282±8 Ma with ~340 Ma peak and minor >630 Ma peak ages of detrital zircons. The spessartine-rich garnet in quartzite is interpreted to result from deep-sea manganese-rich silica-rich sediments (probably chert). Two amphibolites show late Permian/Early Triassic protolith ages (249±7 Ma –266±4.2 Ma).

As a whole, our dating results are entirely unexpected and require a re-evaluation of the tectonic history of the Austroalpine units. Based on the dating results, we conclude that the Plankogel complex represents a Triassic ophiolite-bearing mélange with oceanic trench sediments and components from a deep-sea environment. The detritus is rich in Permian to Middle Triassic volcanic components. The volcanic components indicate the subduction of the Paleotethyan Ocean, and oceanic lithospheric elements were incorporated into the trench sediments.

In the Saualpe, the Plankogel complex is directly overlying the Eclogite-Gneiss unit, which indicates Cretaceous high-pressure metamorphism and subduction of continental crust during Cretaceous plate collision. The Plankogel complex is preserved in the hanging wall of it and incorporates Triassic trench sediments indicating another, older suture. Such scenarios with preservation of an earlier, displaced suture can be explained by displacement during Cretaceous plate collision according to scenarios proposed by numerical and analog modeling (Vogt et al., 2018).

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Quantifying long wavelength signal of uplift in the Alpine foreland basin using low-temperature thermochronology and numerical models

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Low-temperature thermochronology and vitrinite reflectance data from the Swiss Molasse basin suggest approximately two kilometers of exhumation in the Neogene, with no clear difference between the deformed and the undeformed part of the basin. Exhumation of the undeformed Plateau Molasse cannot only be explained by tectonic transport up a basement ramp during the shortening of the Jura, drainage reorganization or glacial scouring. Therefore, exhumation must be at least partly caused by a deep seated process. Exhumation as a result of changes in subduction dynamics can be distinguished from other causes by their long wavelength. To quantify the wavelength of the system, we have generated new thermochronology and vitrinite reflectance data from the central and eastern part of the basin. First results show that the German part of the basin has experienced less exhumation than the Swiss part of the basin. Estimates from marine units at surface outcrops show 500 m of net uplift since deposition in undeformed parts of the basin, while apatite (U-Th)/He age in this part of the basin show exhumation below or close to the detection limit (~1.5 km). Within the Subalpine Molasse exhumation is localized along thrusts, which indicates thrusting between 10 to 20 Ma. To further constrain the thermal history of the basin we model the thermochronology data set using the new open source basin and thermal history model PyBasin. This code takes into account the uncertainty of thermochronometers introduced by different provenance ages. Finally, we discuss different causes of the variable exhumation of the basin and their relation to slab-dynamics during the late stage of the alpine orogeny.

Using thermal springs to quantify deep fluid flow and its thermal footprint in the Alps

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While several studies have shown that meteoric water can penetrate large parts of the crust and can strongly alter subsurface temperatures, the extent and thermal effects of deep fluid flow in mountain belts are still largely unknown. Here we present a newly compiled database of thermal springs in the Alps, which we use to quantify the extent of deep fluid flow and its thermal effects. The database contains temperature and discharge data for 450 springs and hydrochemistry and isotope data for 150 of the springs. We discuss the distribution of springs and the relation with tectonic and seismic activity of the Alps. We present a new heat and fluid flow model code and use this code to inversely model the depth of fluid conduits and faults that feed the springs. In addition, the model is used to quantify the thermal footprint of hot springs and the effects of fluid flow on low-temperature thermochronometers. The modeled maximum flow depth and temperatures are compared with independent estimates based on the hydrochemistry and stable isotope composition of spring water. The results provide one of the first large scale images of deep fluid and its thermal effects at the scale of an orogen.

Metamorphic pressure variation in the Monte Rosa nappe challenges the lithostatic pressure paradigm

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Pressure-temperature-time paths obtained from minerals in metamorphic rocks allow the geodynamic evolution of mountain ranges to be reconstructed under the conventional assumption that rock pressure is static. This lithostatic pressure paradigm allows the metamorphic pressure to be directly converted into the burial depth of the rock and, hence, to quantify the rock's burial and exhumation cycle. In the Monte Rosa nappe, considerably different metamorphic pressures are determined in adjacent rocks from the same coherent tectonic unit. The highest pressure, even if restricted to minor rock volumes, is considered to indicate the minimum burial depth of the entire unit because lithostatic pressure implies that rocks at same depth have same pressure. The lower pressure estimates are explained either by a lack of equilibration of the mineral assemblage during burial due to slow reaction kinetics or by complete retrogression of the high pressure assemblage to lower pressure during exhumation. An alternative interpretation of pressure differences is presented, based on field observations, phase petrology and geochemistry, where outcrop-scale pressure gradients of 0.8 GPa are reflecting transient high differential stress, recorded by mineral assemblages. The results are compared with a simple analytical solution of pressure distribution between rocks with contrasting viscosities to confirm that our interpretation is coherent. If future studies systematically confirm such pressure variations, then current models of collisional orogens and associated metamorphic cycles have to be changed fundamentally.

Deformation history of Ultra High Pressure ophiolitic serpentinites in the Zermatt-Saas Zone, Créton, upper Valtournanche, Western Alps

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Detailed multiscale structural analysis and mapping (1:20 scale) integrated with petrological investigations were used to study a portion of the Zermatt-Saas serpentinites that outcrop in upper Valtournanche (north-western Italy). Results are shown in a foliation trajectory map that displays the transposed original lithostratigraphy of a serpentinite body exposed at Créton. The serpentinite body comprises magnetite-rich and rare centimetre- to decimetre-thick pyroxenite layers and lenses. Moreover, veins and aggregates of Ti-chondrodite and Ti-clinohumite, olivine-rich layers, lenses and veinlets. Serpentinites and associated rocks record three superposed groups of ductile structures: D1 consists of rare isoclinal and rootless folds, associated with S1 foliation; D2 consists of tight to isoclinal folds and a pervasive foliation (S2), which is the dominant fabric at the regional scale; D3 includes a crenulation and shear zones overprinting S2. The microstructural analysis suggests the metamorphic conditions of successive deformation stages (Luoni et al., 2018). The resulting tectono-metamorphic evolution is correlated with those already inferred in surrounding areas (Rebay et al., 2012; Zanoni et al., 2012; Zanoni et al., 2016; Rebay et al., 2018). In addition, metre- to submillimetre-sized pre-D2 structural, mineralogical, and textural relics have been clearly identified in spite of the strong HP-UHP D2 transposition: these relict fabrics are marked by either UHP or hydrothermal oceanic mineral assemblages.

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UHP relics in the Zermatt-Saas Zone serpentinites: insights into a new geodynamic scenario

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Ti-chondrodite (Ti-Chn) and Ti-clinohumite (Ti-Chu) assemblages in the eclogitized serpentinites indicate that UHP conditions are attained, in other localities of the Zermatt-Saas Zone (ZSZ) besides Cignana Unit. This finding changes the tectonic scenario of the northwestern portion of the Alpine ophiolites (Luoni et al. 2018). This recognition has been possible by multiscale structural analysis and detailed mapping (1:20 scale) integrated with a petrological investigation of serpentinites at Créton (upper Valtournanche, north-western Italy). Polyphasic ductile deformation transposed original lithostratigraphy of serpentinites comprising magnetite-rich layers, rare veins of Ti-chondrodite + Ti-clinohumite, olivine-rich and pyroxenite layers and lenses. S2 is the dominant fabric in the region and at Créton; it preserves relics of earlier foliation or isoclinal rootless folds (pre-D2) and is crenulated and intersected by shear zones. Pre-D2 mineralogical and textural relicts are preserved regardless of pervasive development of S2 HP-UHP foliation in serpentinites. Pre-D2 mineral assemblages consist of Cpx or Ol + Ti-Chn+ Spl + Atg ±Chl. Ti-Chn+ Ti-Chu polygonal aggregates (with minor Chl + Ilm + Mag + Atg + Cpx or Ol) can be interpreted as either predating S2 or synkinematicwith the early stages of S2 development (pre- to early-D2). The occurrence of Ol + Ti-Chn+ Spl implies recrystallization under UHP conditions (P = 2.8–3.5 GPa, T = 600–670 °C), similarly to those recorded by the nearby Cignana Unit rocks, where coesite and microdiamondhave been found (Reinecke 1991). Furthermore, the P-T conditions for D2 assemblages at Créton are similar to those estimated for D2 in the surrounding serpentinites, which were dated at 65 ±5.6 Ma (Rebay et al. 2012, 2018). These results, coupled with P-T peak condition proposed in this work, lead to consider that the ZSZ was already buried at depth before 70 Ma and dramatically widen the subduction time span under which ZSZ recorded P-T peak conditions. Such observations support the idea that ZSZ is a mosaic of ophiolitic tectono-metamorphic units, which recorded P-peak conditions in different times, and that were coupled during Alpine exhumation, as suggested by quantitative geodynamic modeling (Roda et al. 2012).

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Deformation- dependent P-T variations within a compositionally heterogeneous shear zone: integration of structural and petrological investigations, U-Th-Pb dating and numerical modelling from Cima di Gagnone (Cima Lunga Unit, Central Alps)

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The Cima Lunga Unit in the Central Alps consists of continental basement rocks (orthogneisses, paragneisses and metapelites) enclosing small inclusions of oceanic crust (eclogites, amphibolites and peridotites). All lithotypes are pervasively folded and sheared during the Alpine orogenic phases, resulting in a high-strained nappe with estimated shear strain γ>10. Since their discovery, the ultra-basic rocks received the major attention as they preserve ultra-high pressure eclogite-facies assemblages with peak metamorphic conditions up to 2.5 GPa and 750 °C in the Cima di Gagnone area. The metamorphism of the host rock –i.e. the gneiss complex –is instead constrained at considerably lower P-T conditions (up to 0.8 Gpa and 660 °C). These contrasting thermodynamic histories rise a major challenge for developing a consistent geodynamic model. The coexistence, at the outcrop scale, of such different metamorphisms implies either extreme mechanical decoupling or extremely variable metamorphic equilibrium during Alpine subduction. Our research addresses the link between metamorphism and deformation focusing on the positive feedbacks of tectonic stress on the development of apparently incompatible metamorphic patterns. We present coupled structural and petrological investigations (thermo-barometry and thermodynamic modelling) with the aim to characterize the possible composition- and stress-dependent variation in metamorphic conditions, as well as their magnitude with respect to the relative position in the inclusion-matrix network. The resulting pressure-temperature paths are temporally constrained with U-Th-Pb dating of monazite, which is crucial to determine the relative timing between metamorphic and deformation processes. Field and laboratory-data are finally compared with the results obtained from elasto-visco-plastic 2D Finite Difference models.

The Alpine puzzle and its link to the Tethyan and Atlantic paleogeographic evolution

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The paleogeographic evolution of the Alpine system in Western Europe has been the subject of numerous scientific debates between different schools. However, none of them can convincingly explain the interaction between the European, Iberian and Adriatic plates during their separation and subsequent amalgamation. Rifting separated strong lithospheric domains (e.g. Adria, Iberia and other micro-plates) and led to strongly extended basins floored by exhumed crust and/or sub-continental mantle or even by proto-oceanic crust. These basins formed as the consequence of multiple rift events from the Triassic in the east (Meliata/Vardar/Eastern Mediterranean), to the Lower-Middle Jurassic (Alpine Tethys: Liguria, Piemonte, Valais) to Late Jurassic and Early Cretaceous to the west (Iberia/Orphan/Biscay/Pyrenees) leading to a final breakup in the southern N-Atlantic domain in Aptian/Albian time. Subsequent convergence initiated in middle Cretaceous in the east (eo-Alpine event >84Ma) before it stepped into the Alpine/Pyrenean system (<84Ma). Two major phases characterized the Alpine domain: a meso-Alpine phase corresponding to the subduction of the Alpine Tethys (84 to 35Ma) and a neo-Alpine phase that was linked to a re-organization and retreat of the subduction in the Mediterranean domain simultaneous with convergence in the Western Alps and Apennines. The Alps s.str. are the cornerstone of this system and resulted from the reactivation of multiphase Mesozoic rift systems during different stages of subduction and collision. In the course of this evolution parts of the Alpine system flipped from a lower to an upper plate position of the active subduction, adding additional complexity to the metamorphic and structural evolution of some domains. Unravelling the jigsaw-like arrangement of the different micro-plates and related timing and kinematics is a complex task and can only be achieved if the Mesozoic paleogeographic evolution of the Tethys and Atlantic rifts/rifted margins are integrated in the Late Cretaceous – Cenozoic convergence between African and Europe. In our presentation we review the paleogeographic evolution of the Tethys-Atlantic systems and discuss, using examples, their role in controlling the subsequent subduction and collisional systems in the Alpine domain in Western Europe.

Greenschist or blueschist facies: the key role of redox conditions for the growth of sodic amphibole in the Dent Blanche Tectonic System (Western Alps)

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The sodic amphibole glaucophane, commonly coloured in blue, is generally considered as the mineral indicative of blueschist-facies metamorphism (i.e. occurring in former subduction zones). However, sodic amphiboles display a large range of chemical compositions, due principally to the $Fe^{2+}Mg_{-1}$ and $Fe^{3+}Al_{-1}$ substitutions. Therefore, the whole-rock composition, and especially the oxidation state of a rock, strongly controls the stability field of the sodic amphibole at the transition from greenschist- to blueschist-facies. Under evaluating this point can lead to the incorrect account of the metamorphic conditions, resulting in a misinterpretation of the tectonic framework of the rocks. This work explores the mechanisms that can explain the scarcity of sodic amphibole and sodic pyroxene within the basement of the Dent Blanche Tectonic System (Western Alps), as the result of the Alpine metamorphic history.
Field, petrographic and geochemical data indicate that sodic amphiboles crystallize in three different rock types. Firstly, in undeformed pods of ultramafic cumulates (hornblendite), sodic amphibole (magnesioriebeckite) forms coronas around magmatic calcic amphibole. Secondly, in mylonitized granitoids metasomatized along the contact with ultramafic cumulates (amphibole-gneiss and albitite), sodic amphibole (magnesioriebeckite-winchite) mainly forms rosettes or sheaves. Only locally the amphibole needles are aligned parallel to the mylonitic foliation and the stretching lineation. Pale green, patchy zoned aegirine-augite is dispersed in an albite-quartz matrix or forms layers of fine-grained fibrous aggregates. Thirdly, sodic amphibole (magnesioriebeckite-glaucophane) occurs with muscovite-epidote-quartz in fine-grained volcanoclastic schists.
Bulk rock chemistry of the different lithologies indicates that sodic amphibole and sodic pyroxene developed in Fe_{total} rich system or in system with a high Fe^{3+} / (Fe^{2+}+Fe^{3+}). Thermodynamic modelling has been performed for different rock types, taking into account the measured Fe_2O_3 contents. This allows exploring the effect of varying the oxidation state ratio and the water content. Results of these numerical models highlight the role of Fe_2O_3 on stabilizing sodic amphibole and sodic pyroxene and suggests that sodic amphibole is stable at ~ 8-10 kbar and 400-450°C, i.e. at the transition between the greenschist- and blueschist-facies.
Our models suggest lower pressures compared to other estimates based on Si content in muscovite and provide better constraints on the Alpine metamorphic evolution of the Dent Blanche Tectonic System.

Argand's work on the Western Alps : a reappraisal

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Emile Argand (1879-1940) built his tectonic synthesis of the Alps progressively, starting around the Dent Blanche massif (1905 to 1909), then extending it to the whole arc of the Western Alps (1911 to 1916), and eventually crowning it all by the global vision displayed in the "Tectonique de l'Asie" (1924). On a conceptual ground we can also follow the gradual steps of the development of his thought: (1) First he established the geometry of the belt (1911), based on very detailed field observations (more then 500 days of effective field work from 1902 to 1908). (2) Then he elaborated a kinematic model of its evolution (1916). (3) Finally he exposed a geodynamical synthesis (1924) that prefigured modern plate tectonics:

(1) Geometry: Argand (1911) demonstrated that the Pennine Alps are formed by the superposition of 6 nappes, transported northwards. This reconstitution resisted remarkably well to one century of ceaseless attacks from various sides. The disputes have been of three types: (a) denial of the allochthony of the object interpreted by Argand as a nappe; (b) challenging its northwards movement, the nappe being rather supposed to have been transported southwards; (c) inversion of the order of superposition of the nappes. Some of these points are still the subject of considerable controversy today. We will briefly discuss a few examples. The main difference between the argandian and modern tectonic reconstitutions is an increase of the number of distinct nappes due to a much better knowledge of Alpine stratigraphy and petrology. This is not an attack against his vision, rather this is going further than him in the direction he had advocated.

(2) Kinematics: Argand (1916) described the building of the Alps by a continuous succession of compressive phases ("embryotectonics") spanning from Carboniferous to the present. After 1950 this reconstitution was severely criticized because of lack of evidence of compressive structures during Triassic and Jurassic. However:

-- In 1916 the age of the Earth was commonly considered to be of the order of a few tens of Ma. Shortening the original width of the Alpine space obviously required more than a few Ma, which obliged to start early in the Earth's history.

-- In his last publications Argand (1934) changed the paradigm: he introduced extensional events during Triassic and Jurassic and concentrated the four main compressive phases around the Oligocene.

(3) Geodynamics: The "Tectonique de l'Asie" (1924) is extremely rich in new ideas. We will only underline a few points:

-- Argand explained the birth of the oceans by extension between two separating continents. The "geosynclinal condition" is a step on the way to the "oceanic condition".

-- Alpine ophiolites are remnants of the "sima" exhumed and extruded by this separation.

-- He explained the origin of the Himalaya by the underthrusting of India below Asia, contrary to the Alps where the southern continent is thrust over Europa.

-- A specificity of Argand's thought is the importance attributed to large-scale plastic rheology.

Spatial variations and quantification of seismic deformation in the Western Alps

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In the Western Alpine arc the far field convergence responsible of the Oligo-Miocene continental collision appears now extinguished from GNSS measurements. However, seismicity and slow deformation are still active. Major tectonic features of the collision phase(s), such as the Penninic Front, are nowadays reactivated in normal faulting. Indeed, geodetic and seismotectonic studies have shown that the inner part of the chain is undergoing transtensional deformation while local compressive patterns are observed in the foothills at the periphery of the arc. The orientations of the deformation found by these two different techniques are usually consistent within their uncertainty.
The aim of the present study is to precisely assess the quantification and regionalization of the seismic stress and strain regimes currently at work throughout the Western Alps. This task is accomplished thanks to a new set of more than 30 000 Alpine earthquakes recorded by the dense local Sismalp seismic network since 1989. We first computed well-constrained focal mechanisms (f.m.) for more than 2 000 events with Ml ranging from 1.0 to 5.0 based on first motion (P-wave) polarity. These events have been localized using a 3D velocity model (B. Potin, 2016). This is the first time that such a huge focal mechanism dataset can be analyzed in the Alps. The global distribution of P and T axes dips confirms a vast majority of dextro-extensive focal mechanisms in the overall Alpine realm. We regionalized these results based on a bayesian interpolation method, providing a probabilistic regionalization of the seismic styles of deformation in the Western Alps. We then used this f.m. dataset to compute and sum seismic moment tensors in homogeneous volumes of crust according to Kostrov's method, to obtain seismic strain rates directly comparable with geodetic ones. This method has been improved using statistical seismic distributions and modeled b-value related distributions. This comparison allows to better assess the regional seismic hazard through the computation of a seismic budget deficit with respect to the GPS-measured deformation.

Plate tectonics versus continental tectonics: A case of Ampferer-type subduction in the Alps and Pyrenees

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More than 100 years after Gustav Steinmann's description of ophiolites and the description of subduction, or "*verschluckung",* by Otto Ampferer, the evolution of the Alpine Orogen from rifting to collision remains controversial. The characteristic geodynamic features of the Pyrenees and Alps are surprisingly distinct from features of *Wadati-Benioff-type* subduction. The latter have large subducted oceanic slabs, a long term magmatic record and intra-oceanic subduction-initiation signatures during the first 20Ma of subduction which include upper-plate extension and magmatism followed by either obduction (Neotethys ophiolites) of formation of mature arc system (e.g. Izu-Bonin-Mariana arc). Other characteristics include the minor abundances (<1%) of high-pressure lithologies in a accretionary prism (e.g. Franciscan Complex, USA) and near-absence of evidence of (ultra-)high pressure lithologies. On the other hand, the Pyrenees and Alps are characterized by amagmatic subduction initiation at passive margins and a pre-collisional lithosphere comprised of rift basins characterized by thinned continental crust, exhumation of subcontinental mantle and oceanic core complexes. The Pyrenees record no magmatism during convergence, whereas magmatism in the Alps is only recorded during collision. This leave a ca. 50-60 Ma gap in the Alps, from subduction initiation to collision, where the detrital zircon record shows no magmatism even though subduction of oceanic and continental fragments reaches ~2 GPa. Moreover, the Alpine orogen shows abundant high-pressure lithologies and coherent imbrication of high-pressure passive margins. In order to resolve these discrepancies, we revive the term of *Ampferer-type* subduction to describe a convergent setting which lacks the foundering of oceanic lithosphere and formation of Pacific-type subduction zone "characteristics". We suggest that convergence was controlled not by spontaneous subduction of oceanic lithosphere but by the forced closure of hyper-extended basins along weakened, serpentinised passive margins. This allows us to distinguish *Benioff-type oceanic subduction* resulting from the efficient subduction of oceanic lithosphere, abundant magmatism and limited exhumation of metamorphic lithologies, from *Ampferer-type continental subduction*, derived from the closure of hyper-extended continental basins, inefficient deep subduction of hydrated (serpentinites and oceanic sediments) lithologies, preservation of high-pressure units and amagmatic characteristics.

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Evidence for a rapid uplift of the migmatitic Gruf complex and mechanical erosion of the adjacent Chiavenna unit (European Central Alps).

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We present a detailed field, petrological and geochemical study along three cross sections from the Chiavenna unit to the migmatitic Gruf complex in the southern part of the Lepontine dome of the Central Alps (Switzerland / Italy).

The Chiavenna unit is mainly composed of metaperidotites, mafic rocks and rare metacarbonates and is interpreted as an incomplete, overturned, ophiolitic sequence representing the remnant of the Cretaceous Valais through. The rocks of Chiavenna unit show a strong metamorphic field gradient characterized by an isobaric increase of the temperature from north to south dated at 30 Ma. In the north, metaperidotites are antigorite-bearing while amphibolite are epidote-bearing. In less than 4 km, towards the south, in the metaperidotites the diopside-out, talc-in, antigorite-out, talc-out, entastite-in and spinel-in isograds are progressively crossed whereas amphibolites progressively bear diopside and show evidence of in-situ partial melting. Mineral isograds are parallel to the contact with the Gruf complex and indicate a thermal gradient of ca. 80°C/km.

The Gruf complex is mostly composed of partially molten ortho- and paragneiss migmatized between 32 and 30 Ma. The northern part of the Gruf complex is characterized by an enclave rich-biotite orthogneiss and rare sillimanite-biotite-garnet paragneiss. The main foliation in the orthogneiss strikes ENE-WSW and displays a NE-plunging stretching lineation. Some shear bands filled by leucosomes indicate a top to the NE sense of shear. However, the most of shear bands are leucosome-free and indicate a top to the SW sense of shear. Enclaves in the orthogneiss are mainly mafic and impregnated of granitic melt from the host orthogneiss suggesting a partially molten state of the orthogneiss during incorporation of the enclaves. The average aspect ratio of the enclaves increases from 2 to 6 toward the contact with the Chiavenna unit. Traces elements compositions suggest, that these enclaves probably arise from the adjacent Chiavenna amphibolites.

Conventional geothermobarometric calcualtions, and P-T pseudo-sections show that migmatitic paragneiss in the Gruf complex were migmatized at T= 700-780°C and P= 7-8 kbar. In contrast, P-T estimates of Chiavenna amphibolites gave T= 650-750°C and P= 4-5kbar. These results show a pressure difference of ca. 3kbar in 600 meters between the two units, which suggests a strong differential uplift of the Gruf complex in respect to the Chiavenna unit. We propose that during the rapid uplift of the Gruf complex, the enclave-rich biotite-orthogneiss was strongly partially molten and acted as a low-viscosity layer accommodating the movement between the two units. Enclaves have been probably incorporated into the orthogneiss during the uplift by mechanical and thermal erosion of the adjacent Chiavenna unit. Rapid uplift of "hot" Gruf complex produced the strong metamorphic field gradient in the Chiavenna unit, which led to the dehydration of the ultramafic rocks. This hypothesis will be tested by hydro-thermo-mechanical modelling.

Towards a new seismotectonic characterization of Switzerland (SeismoTeCH): An overview

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With the advances in earthquake monitoring and processing, accuracy and precision in the localization of hypocenters improved significantly, so that today, location uncertainties can be narrowed down to the sub-kilometer scale (e.g. Diehl et al. 2017). Recent re-processed and re-interpreted 2D and new high-resolution 2D and 3D reflection seismic data as well as geological 3D models provide new insights into the subsurface structural setting of the Swiss Molasse Basin (e.g. Landesgeologie 2017). With swisstopo's harmonization of geological vector data (GeoCover) meanwhile also a more complete structural dataset becomes available. Insofar, the interplay between seismicity and faults can now be investigated in much more detail. Finally, the Global Navigation Satellite System (GNSS) provides increasing data volumes, leading to steady improvements of surface deformation estimates in the Alps.

In the light of these new developments, the Swiss Geophysical Commission has launched a project called "SeismoTeCH" (Seismotectonic Characterization of Switzerland). We present here a first part of this study, where we review the late Alpine evolution and the corresponding tectonic, geodynamic, and seismic setting of the Swiss Alps and their forelands. We present an overview of existing datasets, which we analyze and compare (e.g. spatial and temporal distribution pattern of seismicity, recent crustal velocities, tectonics, focal mechanisms) in order to define regions of similar seismicity pattern, i.e. seismotectonic domains.

Geological mapping, deep and shallow seismic imaging, and seismic tomography reveal that the Alps are highly non-cylindrical along-strike the orogen's axis. This has its origin likely in the paleogeography, which was inverted during the Alpine orogeny, and nowadays conditions the distribution pattern of lithologies. The latter has a significant impact not only on the topographic evolution due to differences in the erodibility of rocks, but also on the tectonic evolution, which is crucially conditioned by the distribution of mechanically weak or strong rocks and the occurrence of inherited structures. Also at depth, the Alps are segmented as has been revealed by deep seismic imaging and seismic tomography studies (e.g. Kissling et al. 2006). These varying structures at the lithospheric scale and the related processes (e.g. isostatic balancing, delamination) have a significant impact on the tectonic evolution of the orogen. It is expected that this segmentation of the Alps leaves also an imprint on the distribution of seismicity. Therefore, a synthesis on the late Alpine orogeny is a prerequisite for the definition of seismotectonic domains and an important contribution to the SeismoTeCH project.

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Upper Carboniferous-Permian tectonics recorded in the Central Mediterranean: an updated revision

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In this presentation an updated revision of the upper Carboniferous-Permian tectonics as recorded in Corsica, Calabria and Tuscany is proposed. We combine our and literature data to document how the sedimentary, tectono-metamorphic and magmatic upper Carboniferous-Permian record fits well fits with a regional-scale tectonic scenario characterized by trascurrent fault systems associated with stretched crustal domains in which extensional regional structures, magmatism and transtensional basins developed. In Corsica, altogether with well-known effusive and intrusive Permian magmatism, the alpine SantaLucia nappe exposes a kilometer-scale portion of the Permian lower to mid-crust, with many similarities to the Ivrea-Verbano zone. The two distinct Mafic and Leucogranitic complexes, which characterize this crustal domain are juxtposed by an oblique-slip shear zone named as Santa Lucia Shear Zone. Structural and petrological data document interaction between magmatism, metamorphism and shearing during Permian in the c. 800-400 °C temperature range. In Calabria (Sila, Serre and Aspromonte areas), a continuous pre-Mesozoic crustal section is exposed. The lower crust portion of such section is mainly made up of granulites and migmatitic paragneisses with subordinate marbles and metabasites. The mid-crustal section includes an up to 13 km thick sequence of granitoids of tonalitic to granitic composition, emplaced between 306 and 295 Ma and progressively affecting upper crustal levels during extensional shearing to end with a final magmatic activity between 295 and 277, consisting in the injection of shallower dykes in a transtensional regime. The section is completed by an upper crustal portion mainly formed by a Paleozoic succession deformed as a low-grade fold and thrust belt, locally overlaying medium-grade paragneiss units, and therefore as a whole reminiscent of the external/nappe zone domains of Sardinia Hercynian orogen. In Tuscany we document, following early hypotheses, how late Carboniferous/Permian shallow marine to continental sedimentary basins characterized by unconformity and abrupt change in sedimentary facies (coal-measures, red fanglomerate deposits) and acid magmatism well fit a transtensional setting with a mid-crustal shear zone linked with a system of E-W trending (in present orientation) upper crust splay faults. We will frame the whole dataset in a regional framework of first-order shear zones network which includes a westernmost Santa Lucia Shear Zone and an easternmost East Tuscan Shear Zone, developed to accomodate Pangea B to Pangea A transformation during Permian.

3D geological modelling of the western Aar Massif (external Central Alps, Switzerland)

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3D modelling of complex and irregular geological bodies is an expanding discipline that combines two-dimensional cartographic and structural data managed with GIS technology. This study presents a complete workflow developed to process geological information to build a 3D model of major stratigraphic and tectonic boundaries. The investigated area is located in the western part of the Aar Massif (external Central Alps, Switzerland) characterized by pronounced topographic (600–<4000 m) and structural relief. The workflow comprises three major steps: (1) generation of 2D polylines in a map view, (2) projection of 2D information onto 3D digital elevation model, (3) construction of tectonic cross sections and (4) interpolation of 3D surfaces. (1) A two-dimensional dataset of polylines has been generated in ArcGIS (10.3.1) defining the starting dataset for the major stratigraphic and tectonic boundaries of the bedrock units. This dataset has been compiled by using: (i) GeoCover vector datasets 1:25 000 of the Swiss Geological Survey; (ii) The Geological Special Map 1:100 000 of the Aar Massif and the Tavetsch and Gotthard Nappes of the Swiss Geological Survey; and (iii) data from literature. (2) With the 3D structural modelling software Move (Midland Valley; 2018.2) the boundaries have then been projected on a digital elevation model (swissALTI3D) with 2 m resolution. (3) The use of geometric arguments as well as structural measurements allows for projection of these boundaries into a dense regularly spaced network of 2D cross-sections. (4) Finally, the surface and cross-sections boundaries can be interpolated by applying 3D projection and meshing techniques resulting in a final 3D structural model. In this workflow, special emphasis is given to detect and quantify uncertainties related to both surface information and its projection to depth, including effective data validation. Generally, steps (2–4) require iterative adaptations particularly in the case of surface areas being covered by glaciers or unconsolidated Quaternary sediments. The workflow presented here offers the chance to gain validation approaches for domains only weakly constrained or with no surface data available, by generating a 3D model that integrates all accessible geological information and background knowledge.

A Cambrian continental arc and its Early Proterozoic hinterland in Eastern Alps: the Wechsel Gneiss Complex

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As known since a long time, the Austroalpine nappe complex of Eastern Alps and Western Carpathians contains two major basement units, which collided during the Variscan orogeny (Neubauer &Frisch, 1993). These include (1) a nearly unmetamorphic Gondwana-derived fossil-rich unit, which represents an Ordovician back-arc unit and a Devonian passive margin; and (2) an amphibolite-grade metamorphic unit, which was fully affected by Variscan amphibolite-grade metamorphism including Devonian, early Variscan high-pressure metamorphism, and which is considered representing, in major portions, a poorly dated magmatic arc system with intermediary and acidic orthogneisses. Among these, the Lower Austroalpine Wechsel Gneiss unit of the Wechsel window shows Devonian pressure-dominated metamorphism in upper greenschist (Müller et al., 1999).

The basement within the Wechsel window comprises three units from base to top: (1) the Monotonous Wechsel Gneiss unit, (2) the Variegated Wechsel Gneiss unit, and (3) the Wechsel Phyllite unit. In the field, albite porphyroblasts represent the most pronounced feature of both Monotonous and Variegated Wechsel Gneiss units (Neubauer &Frisch, 1993).

The Variegated Wechsel Gneiss Unit contains magmatic rocks (hornblende-gneiss, greenschist, acidic orthogneiss) with U-Pb zircon ages between 508 and 523 Ma. In paragneisses and quartzite, the detritus is dominated by several age groups that include euhedral zircons of ca. 490–500 Ma, 550 Ma and detrital components of ca. 1.9 –3.2 Ga, with a pronounced maximum of ca. 2.1 Ga. In one samples only, the detritus is dominated by Devonian –Carboniferous ages (380–300 Ma).

The Wechsel Phyllite unit includes feldspar-rich tuffs, which gives latest Neoproterozoic ages (e.g., 556.5 ±2.3 Ma and 556.5 ±9.7 Ma), whereas other samples bear a significant detrital component with dominant age populations of 450 –550 Ma and 2.5 –2.9 Ma

Consequently, the new age data gives evidence for two stages of continental arc-like magmatism at 500–520 Ma and 550–570 Ma. We speculate on relationships of the continental arc-type magmatism and coeval oceanic lithosphere (Speik complex) of Proto-Tethyan affinity, which is also preserved in the Austroalpine nappe complex (Neubauer &Frisch, 1993 and references therein). The abundant, nearly uniform 2.1 Ga-age signatures calls for Lower Proterozoic continental crust in the nearly source showing the close relationship to northern Gondwana prominent in West Africa and Amazonia (Stephan et al., 2018).

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Provenance studies using detrital minerals: U-Pb zircon vs. detrital white mica applied to the Neogene Sattnitz Conglomerate, Eastern Alps

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Multi-method mineral-based age-dating provenance studies reveal significant information on the source but depend highly on lithologies and fertility of source. In a pilot study, we investigated U-Pb zircon and Ar-Ar white mica ages from the ca. 400 m thick Upper Miocene to Pliocene Sattnitz Conglomerate of the intra-orogenic flexural Klagenfurt basin in Eastern Alps. The suspected catchment draining along fault-controlled valleys in the west is similar to the present-day drainage patterns except the disconnection from the Karawanken Mts. The Klagenfurt basin was filled by two processes including: (1) transversal infill from the overriding thrust sheet (North Karawanken Nappe), which provided mostly Mesozoic carbonates, and (2) axial infill with Mesozoic carbonatic and siliciclastic sedimentary and greenschist- and amphibolite-grade metamorphic rocks of Austroalpine and subordinate Penninic units. These exhuming and uplifting metamorphic pre-Alpine basement and Mesozoic cover successions provide a good overview of potential sources, which are poorly investigated in bedrocks up to now. For the first time, cataclastic clasts testify preferred erosion of cataclastic rocks of fault-controlled valleys. Ca. 178 (sub-)concordant U-Pb zircon ages indicate erosion of mainly Austroalpine and subordinate Penninic (mainly Variscan metagranites) sources. Three grains with ages between 30.00 ±0.54 Ma and 36.0 ±0.8 Ma relate to erosion of plutons along the Periadriatic fault. Four grains with low Th/U ratio metamorphic zircons of Early Cretaceous age testify erosion of Austroalpine amphibolite-/eclogite facies terrains. A few ages ranging from 255.5 ±4.9 to 286.8 ±5.0 Ma with Th/U ratios typical for magmatic rocks indicate Permian magmatism not known in the catchment. A few grains yield classical Variscan ages between 325.5 ±5.0 Ma and 356.1 ±5.6 Ma, potentially from the Subpenninic Central Gneiss of the Tauern window. A major contribution with Ordovician-Silurian ages (408.8 ±6.8 Ma to 492.4 ±7.9 Ma) seems important. The main peak, however, is represented by Panafrican, Cambrian to Cryogenian, age groups (503 ±11 Ma to 686 ±10 Ma). Only rare magmatic rocks of this age group were identified within Austroalpine and Penninic units until now. Because of the large drainage basin covering all Austroalpine tectonic units, the U-Pb zircon age distribution can be taken as representative for the southeastern part of the Austroalpine tectonic unit, and for the clearly different Penninic and Southalpine units.

Single-grain $^{40}Ar/^{39}Ar$ white mica ages range between 28.3 ±3.3. Ma to 341.9 ±5.1 Ma and well reflect the ages of metamorphism in Austroalpine (79 and 122 Ma) and Penninic (28 and 50 Ma) bedrocks. A subordinate age group is between 202 and 252 Ma reflecting extensional processes in the Austroalpine source region.

Together, U-Pb zircon and $^{40}Ar/^{39}Ar$ white mica age patterns constrain entirely different tectonic processes: the U-Pb zircon ages reflect mainly magmatic and very subordinately metamorphic processes, whereas the $^{40}Ar/^{39}Ar$ white mica constrain metamorphism and post-peak exhumation after metamorphism. Consequently, these methods should be used always in conjunction. The U-Pb zircon signature can entirely miss orogenic processes.

Orogen-parallel migration of exhumation in the eastern Aar Massif revealed by low-T thermochronology

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New and published (U-Th)/He data on zircon, apatite and zircon fission track ages, coupled with a statistical inversion method and structural analyses constrain the thermal overprint and exhumation history of the eastern Aar Massif (Switzerland) in massif-perpendicular and along-strike direction. Our results highlight significant diachrony in the timing of exhumation in the along-strike direction. Maximum exhumation rates (~1 mm/yr) were initially located in the central Aar Massif (from ~22–10 Ma), then gradually migrated to the east between ~10 Ma and present, while the central Aar Massif continued to exhume at slower rates (~0.5 mm/yr). The timing and the pattern of exhumation is in agreement with independent kinematic and age constraints from exposed shear zones in the central Aar Massif. This suggests that long-term exhumation-dynamics are mainly controlled by crustal-scale tectonic processes, rather than climate-driven erosion. The observed diachrony in the timing of crustal thickening and exhumation may be due to (i) a convex edge-shaped paleogeography of the lower accreted European plate and/or (ii) along-strike thickness variations of the syn-orogenic sedimentary cover. The post-2 Ma exhumation pattern correlates with levelling-based modern surface uplift rates and with recent seismic activity. Although the Quaternary exhumation signal is certainly influenced by the effects of glaciations, the observed pattern reflects a continuation of non-cylindrical massif "growth" in an eastward orogen-parallel direction and indicates that - although at slow rates - thick-skinned compressional deformation might still be ongoing especially in the eastern Aar Massif. Non-cylindrical massif-growth is likely to also affect other External Crystalline Massifs or orogens, but may be overlooked because studies typically focus on orogen-perpendicular transects.

Geological-structural and metamorphic study of the Southern Dora-Maira Massif in Valmala (Varaita Valley, Western Alps)

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This study presents new field, structural and petrographic data (supported by geological map) on a portion of the southern Dora-Maira Massif (Western Alps), with implications for its tectono-stratigraphic and tectono-metamorphic architecture.
The southern Dora-Maira Massif is a tectonic nappe stack consisting of several continental crust units which underwent (ultra)-high pressure ((U)HP) metamorphism during the Alpine orogenesis. The study area is located in the Valmala Valley, immediately south of the well-known UHP Brossasco-Isasca Unit. Here, from lower to upper structural levels, are exposed a quartz-eclogitic unit (Rocca Solei Unit; RSU) and a blueschist unit (Dronero-Sampeyre Unit; DSU).
At the contact between the RSU and DSU a shear zone has been recognized (here addressed as Valmala Shear Zone; VSZ). The VSZ lower portion is characterized by blocks of metabasite, serpentinite and calchschist, lenticular in shape and up to hundreds of meters in size, embedded in a matrix dominated by micaschist locally rich in carbonates. On the contrary, the upper portion of the VSZ contains blocks of micro-augen gneiss and minor impure marble, lenticular to tabular in shape and up to tens of meters wide, embedded in a matrix of micaschist.
In the DSU, a metasedimentary Polymetamorphic Complex has been recognised on the basis of the occurrence of relict pre-Alpine porfiroblastic garnet, and distinguished from a Monometamorphic Complex mostly consisting of metavolcanic rocks.
The structural setting of the DSU + VSZ is the result of two principal deformation stages (D1 and D2). The D1 is responsible for the development of a HP foliation (S1) marked by Gln + Grt ±Zo ±Ru in the metabasite and Ctd + Grt + white mica ±Gln ±Lws ±Ru in the micaschist. The D2 generates km-scale folds and an axial plane foliation (S2) marked by low pressure mineral assemblages (Act + Chl + Ab ±Czo ±Ttn in the metabasite and white mica + Chl ±Ab ±Czo ±Ilm in the metapelite). Preliminary petrologic data on the metapelites from the DSU constrain peak P-T conditions at ca. 470°C, 19 kbar, in the lawsonite-blueschist facies.

Tectonic and metamorphic frameworks of the Eastern Mediterranean: a preliminary work.

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Based on the experience of the making of the maps of Mesozoic to Tertiary metamorphism in the Alps "Metamorphic Structure of the Alps" (Oberhänsli, et al. 2004, Bousquet, et al. 2012a) and "Tectonic Framework of the Alps" (Schmid et al., 2004, Bousquet, et al. 2012b), where an interplay of data from structural geology and tectonics with metamorphism as well as age data and geophysical information was used to visualize the spacio-temporal geodynamic evolution of this complex orogenic system, we present a new tectonic frame for the continuation from the Alps to the Asia Minor. This map includes the Balkan, Aegean and Turkish realm in Asia Minor including the Carpathians, Dinarides, Rhodopes, Peloponnese, Aegean as well as Pontides and Taurides. The motivation for the compilation of this map is based on new metamorphic and age data especially for the Carpathians, Rhodopes, Aegean and Turkey. A tectonic map of the Carpatho-Dinaride realm that is consistent with a basic scheme of continental and oceanic realms and their structural relation as developed for the Alps was published by Schmid et al (2008): However, the east ward continuation across Asia Minor is missing. With this new general map, we try to solve the problem of the continuation of the different continental and oceanic units from the Balkan over the Peloponnese and Aegean into Turkey and further to Iran. Due to intense neotectonic effects and movements and the Miocene to Neogene basins and volcanics that cover major parts of Turkey this is still speculative. Several small continental units (Menderes, Kirsehir) of Pan African origin, carrying along old metamorphism, are amalgamated along several Tethyan oceanic units and cannot simply be correlated with the Balkan setting.

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A new tectonic subdivision in the Northern Calcareous Alps of western Austria that resolves a 100 year old controversy

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The Northern Calcareous Alps (NCA) are an Upper Cretaceous thrust belt. In the early 20th century, three major units have been distinguished, that are, from bottom to top, the Allgäu-, Lechtal- and Inntal thrust sheets (Fig. 1A). From the very beginning, this subdivision was controversial: The Zugspitze block of the Wetterstein mountains is continuous with the Lechtal thrust sheet toward the NE, but is also seen to sit on top of the Zugspitze thrust that emplaces the Triassic of the Zugspitze on Albian syntectonic sediments. Therefore, a backthrust at the base of Zugspitze block had been proposed. However, the base of the Inntal thrust sheet is very close to the south and emplaces Triassic on Albian sediments as well. The opponents of the backthrust hypothesis suggested the continuity of the Inntal and Zugspitze thrusts.

We present a new structural analysis of the area of the Zugspitze block and the southerly adjacent Inntal thrust sheet. The key results are:

- The Inntal and Zugspitze thrusts have the same structural characteristics –emplacement of Triassic onto the Albian, NW- to NE-directed transport from s-c-fabrics and dm-scale folds.
- To the N and NE, the Zugspitze thrust is dissected and exhumed by the out-of-sequence Obermoos thrust that disappears into a tightly folded zone toward the east.
- As a consequence of (2), the Lechtal and Inntal thrust sheets are part of the same thrust sheet, that is dissected by laterally discontinuous out-of-sequence thrusts.

To avoid confusion of different subdivisions, we propose the following new nomenclature (Fig. 1B; see Kilian and Ortner, 2019 in press, Austrian Journal of Earth Sciences): The **Tannheim thrust sheet** includes the former Allgäu thrust sheet and two windows NW and NE of Innsbruck. The **Karwendel thrust sheet** merges the former Lechtal and Inntal thrust sheets. Westward increasing offset across out-of-sequence thrusts causes emplacement of the **Imst half-klippe** and **klippen**, that are part of the Karwendel thrust sheet.

The age of syntectonic sediments below the thrust sheets supports such a subdivision. The entire Karwendel thrust sheet is emplaced on Albian sediments. Only the Imst (half)klippen west of the WNW-striking Telfs tear fault between Imst and Innsbruck lie on Cenomanian deposits.

The controversy on the tectonic position of the Zugspitze block was unsolvable, because the basic requirements for definition of a thrust sheet were never explicitely formulated. All involved partys implicitely assumed that a thrust sheet should be bounded by a throughgoing thrust on all sides. However, none of the NCA thrust sheets meets this requirement. Instead, thrusts loose offset toward the tips, and end (see, e.g., the Lechtal thrust of Fig. 1; Therefore, we rather use the term ‚thrust sheet‘ instead of ‚nappe‘). The controversy is resolved employing two ideas:

- The distinction of in-sequence thrusts, that always emplace old on young rocks, from of out-of-sequence thrusts, that may also emplace young on old rocks and cross-cut the first.
- Thrusts end laterally.

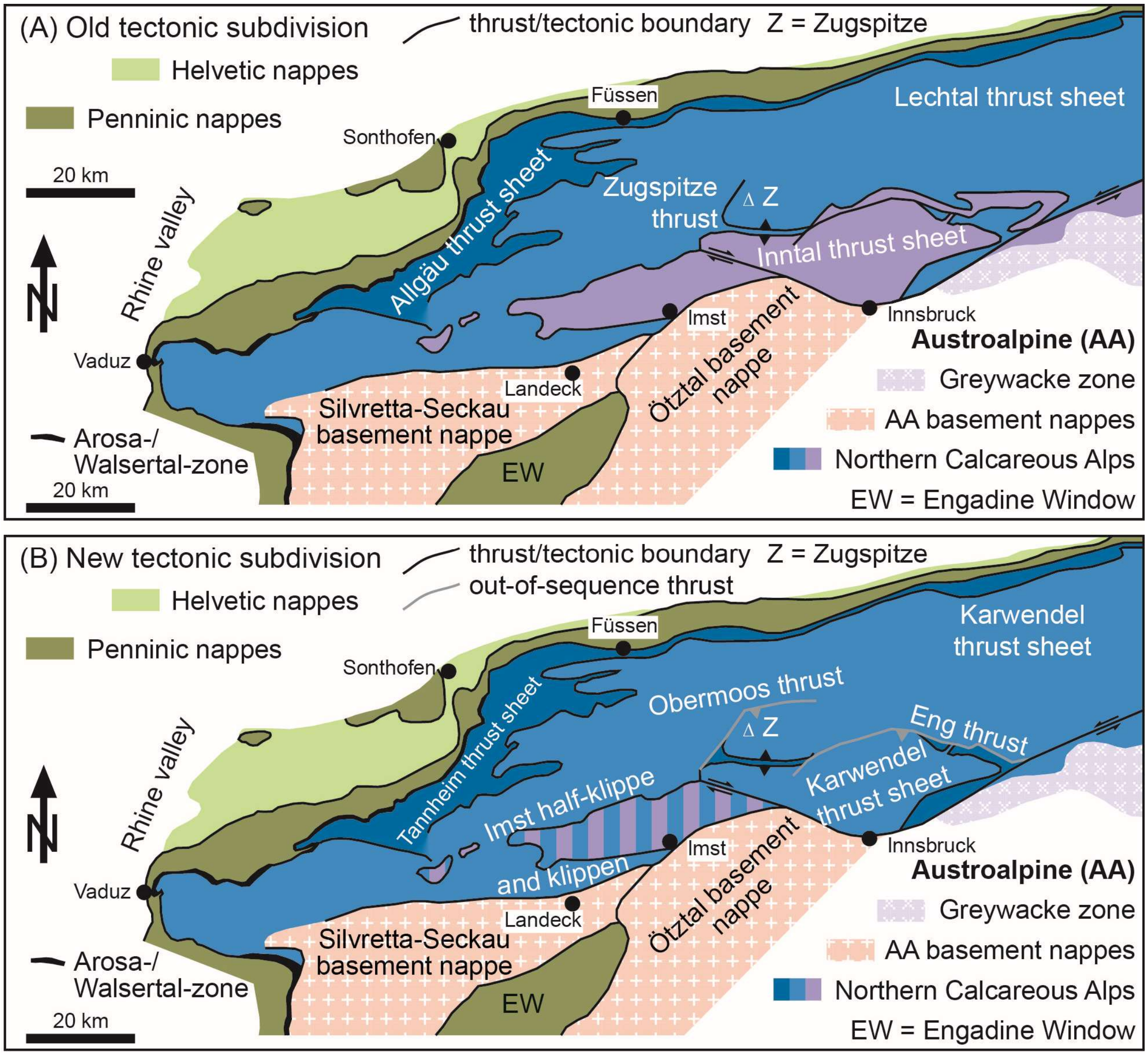

Fig. 1: (A) the old and (B) the new tectonic subdivision of the NCA

The problematic identification of contacts between tectonic units: the example from the Mont Fort and Cimes Blanches nappes (Penninics, Western Swiss Alps)

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The contacts between different tectonic units are commonly highlighted by the presence of distinctive markers such as well-developed mylonitic fabric or intercalation of cornieule level or tectonized slices. In some cases, an abrupt change in the mineralogical assemblages, indicating contrasting tectono-metamorphic histories, may also help to identify such tectonic contacts. When such markers are absent, their recognition can be challenging, especially when two units of similar lithologies are tectonically juxtaposed. On the other hand, the presence within a single tectonic unit, of two levels showing a strong rheological contrast, can lead to local shearing which does not imply a contact between different tectonic units.

In the Penninics of the Alps of Western Switzerland, the location of the boundaries between the tectonic units now called the Mont Fort, Tsaté and Cimes Blanches nappes has been debated for decades. No well-developed mylonitic level are found between these units, while recurrent angular unconformities appear at their contacts. The study we have undertaken show that the upper contact of the Paleozoic levels of the Mont Fort nappe with the overlying Mesozoic sedimentary series, currently interpreted as a nappe boundary, rather correspond to a discordant contact formed by paleofaults during Jurassic extension and passively deformed during alpine orogeny. This Mesozoic series, currently attributed to the Cimes Blanches nappe, constitutes, according to our interpretation, the autochthonous sedimentary cover of the Mont Fort nappe.

This Mesozoic series is discontinuous and is characterised by significant levels of sedimentary breccias, probably Jurassic, ranging from thin turbiditic to coarse debris flows deposits. They are overlying discontinuous levels, attributed to the Triassic and the base of the Lower Jurassic, that consist of quartzites, dolomites and limestones. In few sections, the basal stratigraphic sequence of the Mesozoic series is entirely preserved and lies upon the uppermost formations of the Mont Fort basement with a concordant and non-sheared contact. In other sections where the Mesozoic breccias are found directly on top of the Mont Fort basement, the clasts of the breccia are at places almost entirely identical in composition to the adjacent basement. In addition, all the lithologies observed among the clasts of the Mesozoic breccia can be found in the Mont Fort basement or at the base of the series itself. These observations therefore strongly support the hypothesis of a stratigraphic contact of the Mesozoic series on the Mont Fort basement. This contact would have been cut by significant synsedimentary faults responsible for the sedimentary breccia deposits and recurring angular unconformities. The geological structures observed along this contact and highlighted by our mapping and cross-sections also support this hypothesis, as they are coherent with the passive folding of initial half-graben-type structures.

An intense orogenic deformation can reduce the initial angle of unconformities formed by paleofaults and the resulting discordant contacts may therefore be difficult to distinguish from alpine thrusts.

Deformation microstructures and rheological properties of mantle shear zones: a case study of the Yugu peridotites in the Gyeonggi Massif, Korea

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Large-scale emplaced peridotite bodies may provide insights into plastic deformation process and tectonic evolution in the mantle shear zone. Due to the complexity of deformation microstructures and processes in natural mantle rocks, the evolution of pre-existing olivine fabrics is still not well understood. In this study, we examine well-preserved transitional characteristics of microstructures and olivine fabrics developed in a mantle shear zone from the Yugu peridotite body, the Gyeonggi Massif, Korean Peninsula. The Yugu peridotite body predominantly comprises spinel harzburgite together with minor lherzolite, dunite, and clinopyroxenite. We classified highly deformed peridotites into four textural types based on their microstructural characteristics: protomylonite; proto-mylonite to mylonite transition; mylonite; and ultra-mylonite. Olivine fabrics changed from A-type (proto-mylonite) via D-type (mylonite) to E-type (ultra-mylonite). Olivine fabric transition is interpreted as occurring under hydrous conditions at low temperature and high strain, because of characteristics such as Ticlinohumite defects (and serpentine) and fluid inclusion trails in olivine, and a hydrous mineral (pargasite) in the matrix, especially in the ultra-mylonitic peridotites. Even though the ultra-mylonitic peridotites contained extremely small (24–30 μm) olivine neoblasts, the olivine fabrics showed a distinct (E-type) pattern rather than a random one. Analysis of the lattice preferred orientation strength, dislocation microstructures, recrystallized grain-size, and deformation mechanism maps of olivine suggest that the proto-mylonitic, mylonitic, and ultramylonitic peridotites were deformed by dislocation creep (A-type), dislocation-accommodated grain-boundary sliding (D-type), and combination of dislocation and diffusion creep (E-type), respectively.

Epidote as a potential geochronometer in veins

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Much attention has been paid to the role of fluids in the crystalline continental crust as they mediate mass transfer, and influence chemical and physical processes such as crustal metamorphism. Important and clear evidence of fluid flow are veins at different crustal levels. Epidote, whose potential as a mineral chronometer and geochemical tracer is still poorly known, is a common mineral in veins and represents a promising proxy to unravel their long-term fluid history: (1) Epidote is a robust mineral, given its ability to deform in a brittle manner only without being reset by dynamic recrystallization processes. (2) Given its capability to carry radioactive as well as non-radiogenic trace elements, epidote may serve as both geochronometer and geochemical tracer. We therefore hypothesize that combining (1) and (2) in case of epidote veins might allow us to obtain information on fluid flow far back in time.

To test this hypothesis, we investigated epidote–quartz veins in granitoid rocks of the Aar Massif (Central Alps) and the Albula region (Eastern Alps). To constrain the timing of formation of such veins, we developed an analytical protocol for *in situ* LA-ICPMS U-(Th-)Pb dating of hydrothermal epidote. Such measurements are notably challenging because epidote has low U concentrations relative to well-established U-(Th-)Pb geochronometers, and incorporates initial Pb. In addition, a robust epidote standard for normalization of laser analyses is currently lacking. Our approach uses radioactivity imaging (i.e. a Beta-scanner) in order to target the most promising (i.e. high U and/or Th concentrations) sectors of hydrothermal-vein epidotes for *in situ* U-(Th-)Pb dating by LA-ICPMS. We have chosen to test the suitability of allanite, whose chemical similarity as a member of the epidote group makes it a close match for matrix, and zircon as external standards in spot-analysis mode. We will also assess pseudo-matrix-matched external standards (allanite) versus other well-characterized U-Th-Pb standards (i.e. zircon) and glass by applying dynamic (raster) ablation, hence eliminating possible down-hole fractionation effects.

These different approaches will be evaluated to determine which of them is most suitable for routine epidote dating. Such *in situ* laser data will be discussed in reference to MC-ICPMS bulk measurements of U, Th and Pb isotopes in vein-epidote micro-separates of the same samples. As well as a constraint on the age of vein formation, the measurements permit the determination of the composition of initial Pb, thus providing insight into the source of the fluid. The development of U-(Th-)Pb dating of epidote may provide a valuable new chronometer for dating fluid-related processes recorded in veins from a wide range of geological settings.

Reduced fluids released at sub-arc depth from subducting ultramafic rocks

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Hydrated ultramafic rocks are the main water carrier into subduction zones, thus their metamorphic evolution has a pivotal role in most of the fluid-mediated processes distinctive of subduction settings, such as element cycling, modification of the redox budget of the mantle, arc magmatism, and seismicity. Characterizing the nature of the fluids released from subducting ultramafic rocks is therefore crucial for the better understanding of the geodynamics of our planet.
We combine observations on natural samples with thermodynamic modeling in order to track the evolution of the redox state in subducting, dehydrating ultramafic rocks. Materials representative of the three main dehydration reactions in ultramafic rocks were investigated. In reaction products of brucite-out (Zermatt-Saas; Switzerland) and antigorite-out (Cerro del Almirez, Spain) magnetite coexists with the silicates, whereas at chlorite-out (Cima di Gagnone; Switzerland) Cr-spinel with a minor magnetite component is stable. Thermodynamic modeling shows that these silicate-oxide assemblages can be used as solid-state oxygen fugacity (fO_2) buffer. Our results indicate that the rock during prograde metamorphism evolve from very reduced conditions (4 log units below the Fayalite-Quartz-Magnetite reference value) to relatively oxidized conditions (1 log unit above the FQM buffer) when passing from brucite+antigorite+magnetite to antigorite+olivine+magnetite assemblage. Further oxidation is hampered by the crystallization of orthopyroxene, when the assemblage olivine+orthopyroxene+magnetite buffer the fO_2 to values close to the FQM. At UHP conditions (~2.8 GPa / ~800°C), corresponding to sub-arc conditions, Al-spinel and garnet become stable together with chrome-rich magnetite and olivine, thus indicating that the rock is buffered at 2 to 3 log unit below the FMQ. This has consequences on the stability of redox sensitive phases including sulfides, and fluid composition. Despite limitations in modeling sulfide with the currently available thermodynamic data, results are in good agreement with the observations on natural samples, and point to the overall stability of magnetite together with low S-fugacity sulfides (pentlandite and pyrrhotite instead of pyrite) until UHP conditions are reached. Both petrographic observations and thermodynamic modelling indicate that at the chlorite-out conditions, high temperature and low fO_2 allow for a more significant mobilization of S in the fluid. A major implication is that fluids escape upon brucite and antigorite dehydration do not involve any redox decoupling (i.e., no transport of redox sensitive elements). However, a window of opportunity for S release occurs at sub-arc depth, upon chlorite-out reaction. Importantly, S speciation into the fluid is predicted to be reduced, in the form of H_2S. Such a fluid would act as reducing agent during interaction with overlying altered oceanic crust, sediments or mantle wedge.

Tectonic architecture of the easternmost Bulgarian Rhodopes

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Following a tectonic scheme proposed by Janák et al. (2011; Journal of Metamorphic Geology 29, 317-332) and Pleuger et al. (2011; Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 162, 171-192), the Rhodopes are composed of four nappe complexes, from bottom to top the Lower, Middle, and Upper Allochthon and the Circum-Rhodope Belt. Rocks derived from Adria and/or Pelagonia (Lower Allochthon) are separated from rocks of European origin (Upper Allochthon) by lithologically variegated thrust sheets containing sporadic occurrences of ophiolites (Middle Allochthon). These ophiolites typically yield magmatic protolith ages of c. 160 Ma and were metamorphosed under amphibolite- to eclogite-facies conditions. They represent Neotethyan lithosphere subducted below Europe in the Late Cretaceous to Palaeogene whereas the Circum-Rhodope Belt contains ophiolites of the same protolith age but with lower metamorphic grade (greenschist facies at most) and was obducted onto the former European margin in the Jurassic. We present LA-ICP-MS U-Pb zircon and additional geochemical data from the Luda Reka Unit in the Bulgarian Eastern Rhodopes. This unit consists mostly of amphibolite, metagabbro, and metadiorite that yielded two protolith ages of 163.5±2.6 Ma and 154.2±1.0 Ma. The trace element patterns resemble those of MORB and lower oceanic crustal cumulates but show indications of secondary metamorphic overprint. Initial epsilon Nd values of six samples calculated to 154 Ma were +10.8 ±0.8 (2σ; n = 6), in agreement with average modern depleted MORB basalts. A pegmatite crosscutting the Luda Reka Unit yielded a magmatic age of 52.04±1.1 Ma. Such pegmatites are widespread in the Luda Reka Unit (Middle Allochthon) suggesting that emplacement of this unit over the Bjala Reka Orthogneiss Unit (Lower Allochthon) where such pegmatites are lacking happened only after c. 52 Ma. The Bjala Reka Orthogneiss Unit forms the footwall of the top-to-the-SSW Bjala Reka Detachment that became active in the Late Eocene. Where the Luda Reka Unit is lacking, the Bjala Reka Orthogneiss Unit is overlain by rocks that were collectively described as "Low-grade Mesozoic Unit" (e.g. Bonev &Stampfli 2008; Lithos 100, 210-233). Based on peak temperatures determined by Raman spectroscopy of organic matter, two tectonic units can be distinguished in the "Low-grade Mesozoic Unit". The temperature peak was at c. 530 °C in the Mandrica Unit below and at c. 285 °C in the Maglenica Unit above. For the Mandrica Unit, minimum peak pressures of c. 1.4 GPa were obtained by Raman spectroscopy of quartz inclusions in garnet, indicating that this unit underwent subduction-related metamorphism. Because of this marked difference in peak metamorphic grade, we attribute only the anchimetamorphic Maglenica Unit to the Circum-Rhodope Belt while the high-pressure Mandrica Unit probably represents the Upper Allochthon. Both units are presently separated by the top-to-the-NW Mandrica Detachment that was active before the Bjala Reka Detachment. Our new findings show that the easternmost Rhodopes expose a condensed section through all four nappe complexes, notably including the Neotethys suture.

Recumbent folding in a Late Cretaceous low-angle shear zone between Austroalpine nappes west of the Tauern Window (Brenner Pass area, Austria/Italy)

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The Austroalpine nappes west of the Tauern window comprise the Obernberg Nappe and the Gschnitz Nappe (summarized as Steinach Nappes of the Drauzug-Gurktal Nappe System) tectonically above the Permomesozoic cover (Brenner Mesozoic) of the Ötztal-Nappe (Ötztal-Bundschuh Nappe System) in the footwall of an Eoalpine thrust contact. NW-directed thrusting of the Obernberg Nappe led to a metamorphic overprint of the Ötztal Nappe that attained approximately 500°C in the study area. $^{40}Ar/^{39}Ar$ muscovite ages around 300 Ma indicate that the Obernberg Nappe in the hanging wall of the tectonic contact largely escaped an Alpine overprint. Estimated thermal conditions of up to about 520°C from the Obernberg Nappe (using Raman spectroscopy on carbonaceous material) are attributed to the Variscan overprint. Mixed ages around 260 Ma from the central part of the nappe show an incomplete thermal resetting. Exclusively Late Cretaceous $^{40}Ar/^{39}Ar$ muscovite ages (80 - 90 Ma) were obtained from the southern part of the Obernberg Nappe, indicating a gradually increasing thermal overprint of approximately 450 to 500°C towards the underlying metasedimentary cover of the Ötztal Nappe. Top southeast-directed ductile and ductile-brittle shear sense indicators from the shear zone and a progressively increasing tectonic omission of the Mesozoic sequence towards the southeast evidence a low-angle extensional reactivation of the tectonic contact. Small- and large-scale recumbent folds of the calcitic top of the otherwise predominantly dolomitic metasedimentary succession are seen in the field. $^{40}Ar/^{39}Ar$ muscovite ages (86 - 93 Ma) and a $^{87}Rb/^{87}Sr$ cooling age from synkinematic biotite from the Brenner Mesozoic constrain cooling below 300°C to early Late Cretaceous times. Lenses of highly deformed calcite and dolomite marble within the quartzphyllite of the Obernberg Nappe show lithological similarities with calcite marble from the underlying Brenner Mesozoic. From a reconstruction of the fold geometries, they are interpreted as boudinaged lenses along the axial plane of large-scale recumbent folds that formed during Late Cretaceous low-angle extension.

Garnet water budget in subducted rocks: A case study from the Zermatt ophiolite

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Garnet is a common mineral found in high-pressure metamorphic rocks, formed during prograde dehydration reactions at great depth (>30 km). The structural formula of garnet does not contain any structural OH groups. However, previous measurements have shown that garnet can incorporate significant amount of H_2O (1-10 000 ppm wt. H_2O) (Aines and Rossman 1984a).

Subducted high pressure metamorphic oceanic crust with peak metamorphic conditions of 2.3±0.1 Gpa, 540±20ºC, (Angiboust et al. 2009) crops out in the Zermatt area. There are many different rock types ranging from metacarbonates, pelitic sediments to mafic schists, rodingites, eclogites and serpentinites that host garnet in the main mineral assemblage or in veins and boudins.

We investigated H_2O contents in garnets from these rocks using Fourier transform infrared spectroscopy (FTIR), together with major, minor and trace elements obtained by electron microprobe (EPMA) and Laser Ablation-ICPMS analyses, respectively. Our aim is to quantify the amount of water retained in garnet at 80 km depth in subducted crust and investigate the relationship between garnet/rock chemistry and water incorporation.

The investigated garnets cover an extremely large compositional range. Uvarovite-andradite garnets were found in veins in serpentinites; grossular-rich garnets occur in meta-rodingite boudins and in metacarbonates; spessartine-rich garnets in Mn-metasediments and intermediate grossular-pyrope-almandine garnets of variable compositions in mafic schists, and eclogites.

Determined water contents range from <1 for almandine garnets from metasediments to 5000 ppm H_2O for andradites. We set up a novel approach for the correlation of high-resolution FTIR maps with element distribution maps obtained by EPMA. This method allows to determine if water incorporation and/or retention is enhanced by certain elements, and if H diffusion patterns are visible. The FTIR spectra present different bands according to the chemistry of the garnet, showing that the local environment of H incorporated in garnet is strongly influenced by nearest neighbours. Correlation of FTIR and EPMA maps reveal high correlation between chemical zoning and water zoning. Some garnet compositions are thus more likely to retain/incorporate water. We have established the following affinity for water incorporation: Ca^{2+}-Cr^{3+}/Fe^{3+} garnets >Ca^{2+}-Al^{3+} garnets> Mn^{2+}-Al^{3+} garnets >>>Fe^{2+}-Mg^{2+}-Al^{3+} garnets.

Due to its large P-T stability field, any water incorporated in the crystal structure of the garnet might be transported at mantle depth along subduction zones, and take part to water input in the mantle. Additionally, H principally replaces Si (hydrogarnet substitution) and thus already a few 10's of ppm H2O in the garnet structure might impact on the deformation behavour of deeply subducted crust.

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Constraining deformation phases in the Tauern window, Eastern Alps, using Th-Pb crystallization ages of fissure monazite-(Ce)

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Hydrothermal monazite-(Ce), (LREE,Th)PO_4, hereafter called monazite, is found in Alpine fissures and clefts that formed during Oligocene-Miocene tectonic movements in the Tauern window, Eastern Alps. It was estimated that they crystallized at temperatures of ~200-300°C in the eastern part of the Tauern window (Gnos et al., 2015), thus postdating early fissure formation. Early fissures are oriented perpendicular to the main fold axis (and lineation) of the Tauern window, whereas younger fissures are oriented pependicular to strike-slip faults. However, both fissure generations are sub-parellel.
In a fluid-filled fissure, chemical disequilibrium induced by tectonic movements triggers dissolution of minerals and can lead to crystallization or reprecipitation of monazite and to resetting of the isotopic system (e.g. Grand'Homme et al., 2016; Seydoux-Guillaume et al., 2002, 2012). Therefore, hydrothermal monazite is able to record several deformation events through multiple growth and dissolution episodes (e.g. Bergemann et al., 2017; Berger et al., 2013). Crystallization ages of fissure monazite from the Tauern window were measured at the Nordsim and SwissSIMS facilities. Th-Pb data of monazite growth domains yielded weighted mean ages between 21.3 ±2.1 and 7.69 ±0.88 Ma, indicating protracted deformation over ~14 Ma. N-S shortening between the Northern Calcareous Alps and the Dolomites indenter increases from east to west in the Tauern window and led to folding and exhumation of the European subduction wedge (e.g., Rosenberg et al., 2018). Whereas early monazite crystallization is related to late upright-folding and lateral extension of the nappe stack, younger monazite growth domains predominate in fissures associated with the younger, conjugated strike-silp faults frequent in the central and western part of the Tauern window.
The low amounts of Si, Ca and Y in the dated monazite grains indicate very limited solid solution with huttonite (ThSiO4), brabantite (CaTh(PO4)2) and xenotime (YPO4).
Comparison of Th-Pb fissure monazite crystallization ages to existing crystallization and cooling ages (zircon/apatite fission tracks, white mica ages from fault zones, (U-Th)/He ages; e.g. Bertrand et al., 2017; Schneider et al., 2013) shows that monazite crystallization ages do not show the U-shaped distribution like cooling ages, when plotted on a section perpendicular to the main fold axis of the Tauern window.

Is the Rocca Canavese Thrust Sheet (Italian Western Alps) a subduction-related mélange? A multidisciplinary approach

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In the Sesia-Lanzo Zone (SLZ), the subunit Rocca Canavese Thrust Sheet (RCT) is characterised by a mixture of mantle- and crust-derived lithologies such as metapelites, metagranitoids, metabasics, and serpentinised lherzolite lenses, from metre to hundred-metre size. We use a multidisciplinary approach in order to evaluate whether this tectonic mixture can be interpreted as a former subduction-related mélange in the Austroalpine domain. In particular, we perform a structural and metamorphic analysis of metagabbros, Jd-bearing and Lws-bearing glaucophanites to estimate their P-T-t-d evolution during the Alpine convergence. We also compare the geologic results with the predictions of a numerical simulation of an ocean-continent subduction zone.

Metagabbros and Jd-bearing glaucophanites experienced a D1a metamorphic stage characterised by a pressure of 1.3-1.8 GPa and temperature of 450-550°C, in eclogite facies condition. On the other hand, Lws-bearing glaucophanites experienced a D1b metamorphic stage at a temperature <470° and pressure of ca. 1.2-1.5 GPa, in Lws-blueschist facies condition. The two tectono-metamorphic units (TMUs) were coupled together during the exhumation at D2 stage, under Ep-blueschist facies conditions. Successive evolution occurs at lower pressure, under greenschist facies conditions. D1a peak conditions are compatible with a thermal gradient between a cold and a warm subduction zone, while D1b peak is recorded in a thermal gradient compatible with a cold subduction. The coupling between the two TMUs occurred under a cold thermal gradient, suggesting a still active subduction.

We develop a 2D FEM simulation of an ocean-continent subduction zone in order to verify the tectonic evolution of the two TMUs and estimate the amount of mixing occurring in a subduction-related mélange. The predictions of the numerical model well reproduce the two peak conditions (D1a and D1b) as well as the successive coupling of the two TMUs under Ep-blueschist facies conditions. Interesting, the peak conditions lie along two different P/T gradients. Thus, the two different thermal gradients showed by the two peak conditions can represent two burial paths probably accomplished in different positions within the subduction channel. The amount of mixing estimated in the field well agrees with that predicted by the numerical simulation. According to our multidisciplinary analysis, RCT is a tectonic mixture of recycled crustal slices and hydrated mantle material formed within a subduction channel. The different origin and P-T-d-t paths of the blocks, the intense shearing experienced by all lithologies during their coupling and the abundance of serpentinites in the tectonic mixture agree with the interpretation of a subduction-related mélange for RCT.

A seafloor origin and P-T-time path of eclogitic lenses in the Central Alps (Capoli and Arami)

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Lenses of mafic and ultramafic high-pressure rocks occur within felsic migmatites in the Central Alps. It remains unclear if these mafic/ultramafic slices are derived from subducted oceanic crust, or if they were part of the sub-continental mantle. Additionally, resolving their P-T-time path is crucial to identify the process that exhumed and incorporated the high-pressure relicts within shallower, felsic crust during continental collision.

We investigated two mafic-ultramafic lenses outcropping at Capoli and Alpe Arami in the Central Alps with emphasis on zircon geochronology and geochemistry. The lens of Capoli consists of a chlorite-peridotite (retrogressed from a garnet peridotite) in the core and of a partially retrogressed eclogite at the rim. The inferred protoliths are partially serpentinized spinel-peridotites and layered gabbros. Zircon grains separated from a Fe-Ti-gabbro yield protolith ages of ca. 265 Ma, and have an elevated $\delta^{18}O$ of 9-10 ‰indicating a crustal origin. The age of a few zircon cores from a kyanite-eclogite with a distinct T-MORB composition suggests instead a Jurassic protolith. Together with structural and petrographic observations, these constraints indicate that the mafic/ultramafic sequence was partially hydrated in a seafloor setting of the Alpine Tethys close to the European continental margin. During Alpine subduction the mafic/ultramafic association experienced peak temperature and pressure conditions of ~ 800 °C and 30 kbar reaching fluid-fluxed partial melting, followed by isothermal and anhydrous decompression, prior to the Barrovian overprint. The age of Alpine metamorphism is constrained to 30-35 Ma based on zircon rims with a REE signature indicating HP metamorphism and melting. Alpine zircon rims and garnet have $\delta^{18}O$ values between 5-3 ‰that testify to significant fluid-rock interaction, likely during oceanic alteration of the protolith.

The Alpe Arami lens consists of garnet and chlorite peridotites surrounded by eclogites. The contact between the two rock types is characterised by amphibole and leucocratic veins that suggest partial melting of the eclogite during hydration upon decompression. Rutile thermometry indicate 700-800°C for the high-pressure assemblage. Zircon in the eclogites display multiple growth zones with ages between ~ 31-37 Ma, confirming previous estimates. Inclusions of high-pressure minerals (omphacite and garnet) are predominant in the zircon cores, whereas amphibole and plagioclase are observed in the rims, providing clear evidence for a metamorphic origin of the zircons. This contrasts with previous propositions that the eclogites represent high-pressure crystallisation of mafic melts. This is further supported by the $\delta^{18}O$ of the zircon in the eclogite, which is well below mantle value at 2-3 ‰. This signature is interpreted as inherited from the oceanic alteration of the mafic protolith. A few zircon rims with higher $\delta^{18}O$ are likely related to ingress of crustal fluids during melting and exhumation.

The combined data set reveals diverse protoliths for the mafic rocks in the lenses, but a common evolution at the ocean floor, with significant fluid-rock interaction. Alpine high-pressure metamorphism and partial melting occurred between circa ~37-30 Ma, implying that the lenses became part of the migmatitic continental crust during exhumation.

Geochronology of high-grade blocks of the Franciscan subduction-accretion complex

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The metamorphic history of high-grade subducted rocks provides invaluable insight into the thermomechanical processes active in subduction zones. While subduction in the Alps was terminated by continent collision entailing variably strong overprint of related units, the Franciscan Complex of California records a >150 Myr long subduction history that started at ~175 Ma and ended by transformation into a transform plate boundary (San Andreas fault) without significant metamorphic overprinting. The highest grade metamorphic rocks of the Franciscan Complex of California are found as blocks in serpentinite and shale matrix mélanges. They include amphibolites, eclogites, blueschists, and blueschist facies metasediments. These Franciscan mélanges inspired the subduction channel return-flow model, but other processes (e.g., buoyancy-driven serpentinite diapirism) have also been argued to be concordant with our current understanding of their metamorphic history.

We investigated a suite of metabasite blocks from serpentinite and shale matrix mélanges of the Califonia Coast Ranges to better understand the timing of their burial and exhumation. Our new dataset consists of U-Pb dates of metamorphic zircon and $^{40}Ar/^{39}Ar$ dates of calcic amphibole and white mica. Combined with published geochronology, particularly prograde Lu-Hf garnet ages, we can reconstruct the absolute timing and duration of prograde and retrograde metamorphism of individual blocks. We find: (i) Exhumation from the eclogite-amphibolite facies occurred over a limited range from 165–155 Ma with an apparent southward younging trend. (ii) Exhumation of the blocks was uniform and fast in the eclogite-amphibolite facies with rates of 2–8 km/Myr. In the blueschist facies, exhumation of the blocks was less uniform and slower by an order of magnitude. (iii) The age of amphibole in a metasomatic reaction zone indicates that at least one amphibolite was already enclosed in a serpentinite matrix at ~155 Ma. Considering the entire subduction zone system, the high-grade exhumation temporally correlates with a significant pulse of magmatism in the respective magmatic arc (Sierra Nevada) and termination of forearc spreading (preserved in the Coast Range Ophiolite).

Our findings do not support a steady-state process was continuously exhuming high-grade rocks. Instead the subduction zone system appears to have changed with an eventlike character resulting in exhumation of high-grade rocks enclosed in serpentinite.

A thick-skinned model for a key sector of the Western Southern Alps: Lugano – Lake Maggiore area, N Italy

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The interpretation of thrust belts as thick vs thin-skinned complexes results in a debate facing two opposite views of thrust belts evolution (e.g., Pfiffner 2017). A thin-skinned model generally can imply larger horizontal displacement and shortening than thick-skinned one, drastically changing the reconstructed thrust belt interpretation in terms of palinspastic reconstructions and kinematic evolution. The assumption of one of these two end-member models also impacts other related issues, including: landscape evolution, potential exploitation of natural resources (i.e. water, hydrocarbons, minerals and earthquake hazard assessment (i.e. the characterization of seismogenic sources and estimates of slip rates).
Our study is located in the Mt. Campo dei Fiori area, across the boundary between Lake Maggiore, to the west, and the Generoso basin, to the east. Mt. campo dei Fiori represents a key sector to understand the Alpine evolution as it links the upturned upper and lower crust of Central Southern Alps with the exhumed mantle and lower crust of the Ivrea wedge.
At a shallower depth, this sector is characterized by a complex array of mesozoic basins and swells that played a major role in driving the Alpine deformation, together with older inherited structures related to a variscan and post-variscan tectonic phase.
The main object of this study is the Marzio Fault, a tectonic line that experienced polyphasic reactivation and that lies on the westernmost side of the prosecution Cremosina line.
A series of preliminary cross section show the Marzio Fault is a deeply rooted high angle structure, active since Carboniferous and re-activated by thrusting as a transpressive fault (Casati, 1978). Our interpretation of the Marzio Fault is obtained using a series of geological sections based on a newly surveyed geological data, public seismic lines and well logs (Pieri &Groppi, 1981; ViDEPI 2010), deep crustal architecture inferred from Moho surfaces (Spada et al., 2013) and assuming a fixed-axis fault-propagation folds model (Jamison, 1987; Suppe and Medwedeff, 1990). We solve this structure in thick-skinned view, interpreting it as related to wedge structure rooted at crustal depths. Conversely, different interpretations have been previously proposed in the 90's for this area: from a pure thin-skinned style (Roeder, 1992), to a basement-involved thin-skinned sheet (Schumacher 1997).

Refined Imaging and Modelling of the Ivrea Geophysical Body Through New Gravity and Seismic Data

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The Ivrea Verbano Zone is a unique portion of the Western Alps, lying along the Europe-Adria plate boundary and presenting evidences of continental collision processes. At the surface, widespread outcrops of lower to middle-crustal composition rocks are observed, serving as a rare catalog of Earth's lithosphere samples and properties. Below the surface, a sliver of Adriatic lithosphere is at shallow depth, known as the *Ivrea Gephysical Body*, mainly characterised by gravity and seismic velocity anomalies.
The denser units have been documented by significant positive anomalies on several gravity maps, which all differ from each other in terms of maxima locations and contour shapes, because of heterogeneous and sparse data coverage and interpolation artefacts. We have collected 180 new gravity points by filling the gaps towards homogeneous coverage of 1 point every 4 to 9 km^2. From this more complete dataset, a higher resolution 3D density model is constructed and the associated free-air and Bouguer anomalies have been computed.
Rock sample analyses and geological observations in the area have been used to produce a surface density map, presenting significant deviations from 2.67 g/cm^3 —the standard density value for Bouguer anomaly computation. We have therefore defined a new gravity anomaly product: the Niggli anomaly, by incorporating into the computation the observed *in-situ* densities. This approach allows us to develop a 3D crustal density distribution model, that is consistent with the observed gravity anomalies and the surface densities, bringing the geophysical investigation to the geological observation scales.
In the same area, we have operated a 10-station seismic profile for two years, providing complementary information on the shallow crustal structure. Data is being processed by means of receiver functions analysis to recover the main discontinuities. The new gravity and seismic data products will allow moving towards a joint inversion of these geophysical datasets, by taking into account as well the geological observations in the area.

Quantification of reaction-induced stress for periclase-brucite transformation by mechanical-chemical modelling and HR-EBSD

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Hydration reactions are a fundamental metamorphic process and play a critical role in Earth's tectonics and water budget. Here we examine the hydration of periclase (MgO) to form brucite ($Mg(OH)_2$). Brucite has a significantly lower density (ca 2300 kg/m^3 at 500 °C and 3 kbar) than periclase (ca 3500 kg/m^3 at 500 °C and 3 kbar). If the replacement of periclase to brucite takes place under isochoric conditions, a significant pressure increase may occur around the site of mineral transformation. To investigate this phenomenon, we studied a rock sample from the Adamello region (Italian Alps), which exhibits brucite embedded in calcite. Previous studies showed that the brucite has formed by periclase hydration and that the encompassing calcite is extensively fractured. A potential scenario for this fracturing is that the volume increases during brucite formation generating a pressure increase in the brucite, hence reaction-induced differential stress in the surrounding calcite leading to fracturing. To test and quantify this scenario, we perform two-dimensional numerical simulations of the mechanical-chemical coupling during the hydration of periclase to brucite, which is embedded in calcite. We assume that hydration is dominated by a diffusion process. For the equation of state (EOS), the derivatives of density with respect to pressure (compressibility) and to MgO-concentration are calculated directly from the phase-diagram section for the MgO + H_2O - $Mg(OH)_2$ system at 500 °C. Diffusion of MgO-concentration is calculated with a linear diffusion equation including a sink term which causes a decrease in MgO-concentration and mimics hydration. The density variation in the EOS is coupled to the mass conservation equation. The pressure in the EOS is coupled to the elastic-compressible Stokes equations for slow flow of a linear viscous fluid mimicking creep of the periclase, brucite and calcite. The simulations show a pressure increase in the brucite and high deviatoric stress in the calcite at the contact with the brucite. The numerical results are compared with residual stress estimates in the calcite, which have been obtained from high-resolution electron backscatter diffraction (HR-EBSD) analysis. HR-EBSD measurements show that the maximum shear stress in the calcite was ca. 500 MPa and decreases away from the contact. The numerical results of mechanical-chemical coupling can explain the HR-EBSD data suggesting that significant differential stress is generated by hydration reactions in natural rock. Our results show that pressure can locally deviate from the lithostatic pressure, which may have considerable implications for using the metamorphic rock record for the reconstruction of the burial and exhumation cycle of tectonic rock units.

Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey

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We present a map that correlates tectonic units between the Alps and western Turkey accompanied by a text providing access to literature data, explaining the concepts used for defining the mapped tectonic units, and some first-order paleogeographic inferences. Along-strike similarities and differences of the Alpine-eastern Mediterranean orogenic system are discussed. The map allows (1) for superimposing additional information, such as e.g., post-tectonic sedimentary basins, manifestations of magmatic activity, location of ore deposits, onto a coherent tectonic framework and (2) for outlining the major features of the Alpine-eastern Mediterranean orogen. Dinarides-Hellenides, Anatolides and Taurides are orogens of opposite subduction polarity and direction of major transport with respect to Alps and Carpathians; polarity switches across the Mid-Hungarian fault zone, a suspected former trench-trench connecting transform fault. The Dinarides-Hellenides-Taurides (and Apennines) consist of nappes detached from the Greater Adriatic continental margin during Cretaceous and Cenozoic orogeny. Internal units form composite nappes that passively carry ophiolites obducted in the latest Jurassic–earliest Cretaceous (in the case of the Dinarides-Hellenides) and during the Late Cretaceous (in the case of western Turkey) on top of the Greater Adriatic margin successions. The ophiolites on top of composite nappes do not represent oceanic sutures themselves, but root in the Neotethys suture zone that formed well after obduction. Suturing between Greater Adria and the northern and eastern Neotethys margin occupied by the Tisza and Dacia mega-units and the Pontides occurred in the latest Cretaceous along the Sava-Izmir-Ankara suture zone. The enigmatic Rhodopian orogen is interpreted as a deep-crustal nappe stack that formed in tandem with the Carpatho-Balkanides fold-thrust belt, now exposed in a giant core complex that became exhumed in late Eocene to Miocene times from below the Carpatho-Balkan orogen and the Circum-Rhodope unit. Its tectonic position is similar to that of the Sakarya unit of the Pontides. We infer that the Rhodope nappe stack formed due to north-directed thrusting. Both Rhodopes and Pontides are suspected to preserve the westernmost relics of the Paleotethys suture zone.

Calculated and measured elastic properties of rocks for a representative cross section through the Western Alps

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Seismic imaging methods provide an increasingly higher resolution towards greater depth. However the geotectonic interpretation of these images is only possible with precise data on petrophysical properties (e.g. elastic anisotropies) of the rocks involved. In the olivine dominated mantle, the anisotropies mainly result from the strain-induced crystallographic preferred orientation (CPO) of olivine. In the polymineralic crust the situation is more complicated. CPOs of all constituent mineral phases largely contribute to the overall seismic anisotropy of the rocks.
In the context of the international AlpArray/4D-MB-project, this study focuses on collecting anisotropy data of different lithologies involved in a representative cross section through the Western Alps. The Western Alps display a wide variety of metamorphic and unmetamorphic rocks from diverse structural levels of the earth's crust and upper mantle as well as of different paleogeographic origins. In order to obtain representative elastic anisotropies from oceanic crust, continental lower crust and upper mantle, samples were collected from three different locations in the Italian Western Alps. In the Lago di Cignana area, eclogites and blueschists of oceanic origin (Zermatt-Saas-Zone) are exposed next to metasediments of the Combin-Zone. Near Finero we sampled lower crustal rocks and mantle peridotites of the Ivrea Zone and in the Val Strona, a variety of felsic lower crustal stronalites and a marble sample were collected.
The CPOs of the constituent mineral phases of these samples were measured at the Joint Institute for Neutron Research in Dubna (Russia) using time-of-flight neutron diffraction, to gain representative bulk textures. Using these CPOs, the volume percentage of the respective mineral phases in the sample, and single crystal elastic anisotropies, the petrophysical properties of the samples were modelled. The samples can be devided into felsic and mafic samples, with felsic samples displaying P-wave anisotropies between 4.1% and 5.9%, while mafic samples show anisotropies between 1.1% and 3.8%. The P-wave velocities in the felsic samples range from 6.5 km/s to 7.2 km/s, those in mafic samples from 6.8 km/s to 7.8 km/s. Highest P-wave velocities in mica-rich felsic samples are distributed in the foliation plane, while highest velocities in mafic samples concentrate in liniation direction. Furthermore experimental P- and S-wave velocity-measurements were conducted at the CAU in Kiel (Germany). These experimental velocities were measured under confining pressures of up to 600 MPa. Calculated and experimentally measured mean velocities are similar, but anisotropies are significantly higher in the experiments, probably due to incompletely closed microcracks.

The East Variscan Shear Zone in the Western Alps: new insights from the Argentera and the Aiguilles Rouges External Crystalline Massifs

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Recent models of the Southern European Variscan Belt propose the existence of a regional-scale right-lateral transpressive fault known in the literature as East Variscan Shear Zone (EVSZ, Matte, 2001; Corsini and Rolland, 2009). According to this model the EVSZ involved the future Alpine External Crystalline Massifs. The EVSZ in the Western Alps is actually not completely understood, and its role during the Variscan and post-Variscan time is still debated. According to some Authors, shear deformation along the EVSZ is related to the transition between Pangea B and Pangea A active since Permian (Muttoni et al., 2003, 2009).

In order to verify the extension and the timing of the EVSZ in the Western Alps we investigated the structural setting and the kinematic of the flow in two regional-scale shear zones: the Ferriere-Mollières Shear Zone, in the Argentera Massif, and the Emosson-Val Berard Shear Zone, in the Aiguilles Rouges Massif. U-Th-Pb petrochronology on monazite was performed in order to contrain the age of the deformation.

The results higlight a dextral pure shear-dominated transpression active during Variscan time between ~340 Ma and ~320 Ma started under amphibolite-facies metamorphic conditions. Our data confirm that the Alpine External Crystalline Massifs were part of the EVSZ and that its activity is related to Carboniferous transpression and not to post-Variscan deformation. This regional-scale discontinuity influenced post-Variscan tectonics as an inherited crustal discontinuity (Ballèvre et al., 2018) and has implications on the original position and provenance of crustal blocks subsequently involved in the rifting, during Pangea break-up and Alpine collision.

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3D numerical modeling of nappe formation applied to the Western Helvetic nappe system

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The Helvetic nappe system of the Western Swiss Alps formed during the Alpine orogeny by the deformation of half-grabens in the European passive margin. This system exhibits both thin- and thick-skinned tectonics. Several studies on the mechanics of fold and thrust belts agree that the rheology of the basement-cover sequence and the mechanical layering of the sediments have a major impact on the deformation style of thin- and thick-skinned systems. Previous results from two-dimensional numerical models have shown that the viscosity ratio between the basement and the sedimentary cover, together with the depth of the brittle-ductile transition strongly control the deformation behavior. In addition, field observations for the Helvetic nappe system indicate that the bulk deformation of many nappes was dominated by ductile creep. Nevertheless, two-dimensional numerical models and cross-sections are not sufficient to fully comprehend the formation of nappes, because they neglect stratigraphic and structural variations in three-dimensional (3D) space. For example, lateral variations in the depth of half-grabens or thickness ratios between incompetent and competent layers have a strong effect on the deformation style. In order to investigate the effect of lateral variations of half-graben depth on nappe formation, we employ 3D thermo-mechanical numerical modeling with a viscoplastic rheology. Our aim is to constrain the impact of (I) lateral variation of half-graben depth and (II) temperature gradient on nappe formation during continental collision. We model the formation of a 3D accretionary wedge by the application of velocity boundary conditions with a velocity discontinuity. This approach provides a bulk deformation similar to typical sandbox models of accretionary and orogenic wedge formation. In order to quantify the deformation we compute the 3D finite strain tensor for every grid point. From the 3D finite strain tensor we calculate the strain magnitude and the principal strain orientations. Both parameters can be used to identify strain partitioning and deviations from bulk pure shear strain, and particularly gradients in finite strain along lateral directions.

Sampling rifted margins in Alpine-type orogens: role of rift-inheritance and implications for subduction initiation and orogen architecture

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Relics of rifted margin and oceanic basins are present in many collisional orogens as a partial testimony of the conditions at the onset of orogeny. In spite of being recognized as one of the key parameters controlling the evolution and tectonic style of mountain belts, the impact of inherited mechanical properties of the lithosphere is still poorly constrained.

We compiled regional maps and built geological cross-sections across two Alpine-type orogens with different deformation histories, the Western Pyrenees and Western Alps, to show the sampling of rifted margin remnants during convergence. Despite an additional metamorphic overprint in the Western Alps, relics occurring in the internal parts of both orogens are comparable and consist in thin continental crust, exhumed subcontinental mantle, and minor magmatic additions characteristic of present-day distal "hyperextended" rifted margins. Based on both examples, this contribution aims to show how far rift-inherited parameters (i.e. rheology, thermal state, size and maturity of the system), could have controlled the location of subduction initiation and the fate of Alpine-type orogens.

The partial preservation of the pre-orogenic rift system of the Pyrenees along the Bay of Biscay rifted margins provides hints on subduction initiation modalities. Seismic interpretations suggest that most of the deformation was accommodated near the boundary between the exhumed mantle domain and former hyperthinned crust, resulting in the formation of a crustal accretionary wedge with increasing shortening. As similar interpretations can be made in the Alps, we suggest that subduction initiated in the former Continent-Ocean Transition in both cases.

These observations can be explained by the progressive oceanward embrittlement of the hyperthinned crust and serpentinization of the exhumed mantle evidenced at present-day rifted margins. Due to this crustal embrittlement, no decoupling prevails between the upper and lower crust whereas the serpentinization of the underlying mantle represents the main decoupling layer that can control the location of subduction onset. The presence of this inherited rheological weakness can explain the partial sampling of former hyperextended domains within the orogenic wedge of Alpine-type orogens while the rest can be underthrust. Eventually, our interpretations of the deep structure of these Alpine-type orogens suggest that the crustal root imaged by seismic techniques partly represents the subducted portions of former hyperextended domains.

High volumes of mineral dissolution by localized fluid pulses in UHPM metasediments of Lago di Cignana, Western Alps

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Fluids play a key role in many geological processes across a wide range of scales. One of the major challenges in establishing the full extent of the impact of fluids derives from partial replacement of minerals by dissolution-precipitation leaving gaps in the rock history record. Finding the records of such processes can help in understanding and reconstructing the processes of fluid flow, mineral dissolution and related bulk volume changes in rocks.

The UHPM Lago di Cignana Unit (Zermatt-Saas Zone, Western Alps) has been intensively studied for being one of the few localities where coesite- and diamond-bearing oceanic lithosphere has been exhumed. Here, schistose quartzite hosts coesite-bearing garnet and contains lenses of garnetite, which previously have been attributed to local bulk compositional differences. Almost the entire quartzite consists of a retrograde mineral assemblage, so any process occurring during subduction is best recorded in garnet.

Here, we combine a petrological study of both major and trace elements with microstructural analysis based on electron backscatter diffraction to understand the effects of fluids on this system and how they have affected both lithologies.

The compositional zoning in cores and mantles of garnets in both rock types displays evidence for high amounts of dissolution. This is especially pronounced in the garnetite domains, where garnet displays clear dissolution textures which suggest that, besides garnet, a significant amount of associated rock-forming minerals has been dissolved. We interpret the garnetite lenses as accumulations of garnets from adjacent host rock. These were concentrated by the removal of matrix minerals by dissolution, which occurred preferentially along fluid pathways. As fluid pulses converted the metasediments into garnetite, the localized volume decrease can exceed 96%. The extreme extent of dissolution in these metasediments is marked by the garnetite lenses, however, in other rocks, this process may not be as obvious if it is not localized or occurs to in a lesser, yet still significant extent.

Deep subduction of the Monte Rosa unit? New structural and metamorphic results from the upper Val d’Ayas, Italy

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The Monte Rosa nappe consists of pre-Variscan paragneisses, which were intruded by Permian-age granitic bodies. The current position of the basement complex resides within the collisional Austroalpine-Penninic wedge, and derives originally from the upper crust of the pre-alpine distal European passive margin. During the Alpine orogeny, the Monte Rosa incurred a high-P imprint interpreted as subduction of continental crust below the overriding Austroalpine units. The peak pressure conditions for subduction have been inferred from “whiteschist” bodies (chloritoid, talc, phengite, quartz ±kyanite/garnet) that occur as local hydrothermal alterations within the metagranite throughout the nappe. Recent studies revealed peak conditions for these whiteschist bodies are between 2.2 and 2.5 GPa and ~570 ºC. However, locally the host metagranite exhibits ca. 1.4 GPa and ~550 ºC. The reasons for this disparity in peak P are currently disputed and need to be further investigated. This is essential for the reconstruction of the tectonic history of the Monte Rosa nappe, in order to confirm whether pressure of ca. 1.4 GPa (~48 km lithostatic depth) or ca. 2.4 GPa (~82 km lithostatic depth) is representative for the maximum burial depth of the nappe. We will present: (i) new detailed structural geological maps of the Monte Rosa basement exposed at the Mezzalama field area, upper Ayas valley, N. Italy and (ii) new petrological data from basement metapelite samples in close proximity to the high-P whiteschist bodies.

Detailed structural analysis in the study area shows strong strain partitioning within the metagranite. The highest strain intensities are present: (1) near the intrusion-country rock contact, and (2) surrounding the high-pressure whiteschist lenses. Several phases of deformation are observed from early top-N weak augen gneiss shear zones to later top-S mylonite shear zones associated with intense folding. Large areas of the metagranites are undeformed and show pristine magmatic textures, even preserving original intrusive contacts with country rock metapelites, indicating the structural coherence of the Monte Rosa nappe in this study area. Here, we have collected samples of basement metapelites for detailed petrological analysis in order to verify peak Alpine metamorphic conditions. The metapelitic samples preserve equilibration at peak Alpine conditions with limited retrogression, consisting of a unique mineral assemblage: muscovite, paragonite, chloritoid and staurolite. The absence of kyanite and garnet in this assemblage allows us to constrain metamorphic conditions between 1.4-1.7 GPa and ~590 ºC. We have also undertaken preliminary analysis on mineral assemblages from the same samples consisting of garnet, muscovite, paragonite, chlorite and quartz. Metamorphic conditions have been calculated between ~1.4 GPa and ~580 ºC. These results consistently highlight a pressure disparity of 0.5-0.8 GPa when compared to estimates for whiteschist assemblages (negligible temperature differences). Our hypothesis is that the whiteschist represents an area of local overpressure deviating from lithostatic. The consequences this has on the reconstruction and emplacement of the Monte Rosa nappe within the Alpine orogeny needs to be further investigated.

Structures and kinematics of Neogene deformation from the Southern Alpine orogenic front to the Northern Giudicarie Belt (eastern Southern Alps, Northern Italy)

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The eastern Southern Alps are part of the deformed leading edge of the Adriatic plate indenting the European plate to the north. Neogene deformation in the eastern Southern Alps is partitioned into three, kinematically linked fold-and-fault systems: (1) The Giudicarie Fault and its related fold-and-thrust belt, (2) the Valsugana Thrust System and (3) the external thrust-and-fold systems of the orogenic front, including the Schio-Vicenza Fault.
The Schio-Vicenza Fault, is a steep fault system that trends NW-SE, perpendicular to the strike of the frontal thrusts of the eastern Southern Alps. New cross sections on either side of this fault extending from the orogenic front towards the Northern Giudicarie Fault reveal lateral variations in structural style and amount of Neogene shortening
East of the Schio-Vicenza Fault, the orogenic front of the eastern Southern Alps comprises the Bassano thrust system, which is inferred to root in the basement and is associated with an ENE-WSW trending ramp anticline that affects the entire Mesozoic sequence, as well as Mio-Pliocene sediments. Southwest of the Schio-Vicenza Fault, the orogenic front comprises the Marana Thrust, which exposes pre-Permian metamorphic basement in its hanging wall. The basement reaches shallower levels SW of the Schio-Vicenza Fault compared to the NE, which can be related to Mesozoic activity of the Schio-Vicenza Fault that formed the Recoaro structural high. This shallow basement, the Recoaro high, underlies a thin Mesozoic to Paleogene marine to volcanoclastic sequence. Fault-slip analysis of the Marana thrust and ENE-WSW trending fold axes in the Bassano and Marana systems indicate NNW-SSE shortening.
The steep fault surfaces of the Schio-Vicenza Fault system carry two generations of striations: (1) older subhorizontal striations with dominantly sinistral slip indicators; and (2) younger SW-dipping striations indicating oblique downthrow of the SW block. Faults with the Schio-Vicenza trend can be traced NW to the SW end of the ENE-WSW-trending Valsugana Thrust. However, the Schio-Vicenza Fault does not merge with or truncate the Giudicarie Belt. Fault-slip analysis of the sinistral striae yields oblique sinistral strike-slip.
Sinistral motion along the Schio-Vicenza Fault indicates that it acted as a clutch to accommodate differential Neogene-to-recent shortening. NNW-SSE directed shortening was greater NE of the Schio-Vicenza Fault along the Bassano Thrust system (minimum of 14 km) than SW along the Marana Thrust (minimum of 3 km). The observation that the Schio-Vicenza Fault terminates in the NW, near the end of the Valsugana Thrust, rather than merging with the Giudicarie Belt indicates that the latter was kinematically decoupled from Neogene shortening along the orogenic front. Together with the anomalously low seismicity just north of the Valsugana Thrust, this suggests that ongoing shortening is taken up between this thrust and the active thrust front. The oblique normal motion along the Schio-Vicenza Fault is inconsistent with Neogene Alpine shortening and may reflect extension in the foreland bulge of the Apennines.

Crustal reworking and hydration: Insights from an oxygen isotope study of high pressure rocks (Sesia Zone, Western Alps)

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Exhumed portions of subducted crust provide the only direct observational evidence for investigating the fluid flow within and out of the descending slab. The Sesia Zone consists of accreted continental fragments of polymetamorphic and monometamorphic lithologies such as metagranitoids, metasediments and metabasites that experienced pre-Alpine amphibolite to granulite facies metamorphism and blueschist to eclogite facies metamorphism during the Alpine orogenic cycle. Because the granulitic protoliths were inherently anhydrous, the formation of hydrous eclogitic assemblages necessarily required addition of water either during the pre- or early-Alpine evolution. Reconstructing the conditions of the hydration stages can shed light on the dynamics and potential drivers of crustal reworking.

An approach that combines petrology and geochronology with the study of oxygen isotope and trace element geochemistry has been applied to different lithologies from the Eclogitic Micaschist Complex (EMC). Garnet, which mainly forms by dehydration reaction, shows a variety of textures with major and trace element compositional zoning not always reconcilable with simple growth zoning, but also indicating resorption and replacement processes driven by fluid influx. However, the origin of the fluid and the degree of fluid-rock interaction remain largely unknown.

Garnets in metasediments show a notable decrease in $\delta^{18}O$ values of up to 5.5 ‰from the pre-Alpine cores to the Alpine rims. Chronology and trace element patterns of zircon and allanite as well as trace elements in garnet corroborate Permian high-grade metamorphism overprinted by Alpine high-pressure metamorphism, and hint to Triassic reworking at low-grade metamorphic conditions. Texturally, subsequent pulses of externally derived fluids are related to fracturing and resorption of pre-Alpine garnet, new growth of high-pressure garnet and late atoll garnet formation with pervasive growth of phengite, with a distinct $\delta^{18}O$ signature. On the other hand, garnets in metabasites have a typical growth zoning, locally affected by late replacement textures that show no significant isotopic shift in $\delta^{18}O$ composition and are therefore ascribed to internally buffered fluids.

Petrological and isotopic modelling is used to investigate two possible scenarios: (1) the interaction with sea-water during Triassic rifting or (2) the pervasive input of fluids derived from dehydration of mafic and ultramafic rocks during Alpine subduction.

Timing of brittle deformation in the Jura mountains revealed by U-Pb calcite dating

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The Jura fold and thrust belt makes up the northern external part of the Alpine orogeny and formed as deformation propagated from thick-skinned to thin-skinned during the (on-going) collision of the European and Adriatic plates. The structures within the Jura fold-and thrust belt propagated from south to north during the mid-late Miocene. We address the timing, rates and duration of fault propagation and folding in the Jura. Here, we use the recently developed calcite U-Pb dating method to provide direct timing constraints for calcite crystallisation in fractures and as slickenfibres along structures. Samples from the NE internal Jura were characterised using Cathodoluminescence and Electron Backscatter Diffraction imaging and dated using the in-situ laser ablation ICP-MS technique. Laser maps were used to illustrate elemental distribution (U, Pb) within calcite veins and single calcite crystals and target zones for U-Pb analysis. The studied calcite veins have low heterogenous U contents (typically ≤0.5-5 ppm) and yield a spread of ages between Upper Cretaceous to Paleocene (87.2 ±6.7 Ma to 65.1 ±2.2 Ma), and early to late Miocene (18.1 ±1.6 Ma to 10.3 ±0.5 Ma). Sedimentation of the host rock occurred between 163–145 Ma. Our younger calcite veins preserve evidence for multiple periods of later fracturing and fluid flow events. Even within a single vein, two separate events are preserved with a hiatus of >60 Ma. This study highlights the complexity preserved within carbonate veins and provides insights into the potential for calcite to preserve evidence of multiple processes from early diagenesis, to fluid-migration and deformation through fracturing, folding, faulting and vein crystallisation events. The ages reported here provide direct constraints on the timescales for the deformational history of the Jura. Furthermore, our results contribute to the understanding of the structural evolution and rates of formation of fold and thrust belts.

Restoring the Deep Structure of the Tethys Subduction Belt with Lithospheric Profiles in the Alps and Betic Cordillera

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Both the European Alps and the Betic Cordillera orogenic systems formed during the subduction and closure of the Western Tethys ocean. Although various published lithospheric profiles are available for the Alps, with different interpretations of the deep structure (e.g. folded mid-crustal detachments, buried hyperextended crust, lower crust duplexing etc.), few lithospheric profiles are available for the Betics. Furthermore, the Iberian rifted margin geometry is poorly understood and the Africa-Iberia subduction history is controversial. To address these issues, we have reconstructed at a crustal scale both the European and Iberian rifted margins in the Alps and Betics, respectively.

Using area balancing techniques we restored and compared 10 lithospheric profiles in total. Assuming a European rifted margin template with reasonable crustal thickness values (i.e. 30 km foreland and proximal domains, 20 km necking domain, 10 km distal domain, and 15 km outer domain), the recent lithospheric profile by Schmid et al. 2017 in the western Alps provides the best-fit restoration for each crustal domain, with a 380 km wide rifted margin. Using new lithospheric profiles we have restored the Iberian rifted margin for the first time; the central Betics had a 260 km wide rifted margin.

The amount of convergence in the Alps (640 km) and Betics (300 km) was enough to subduct the entire European and Iberian hyperextended margins, and to explain the Paleogene history of high-pressure metamorphism recorded in both orogens. Future work will test the restorations with 2D thermo-mechanical numerical modelling to understand how variations in paleogeography and rifted margin structure influenced the Tethys subduction belt.

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High to ultra-high pressure metamorphism in the Alpine orogeny: Challenges and controversies

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Depending on observed parageneses, the pressure-temperature (*P-T*) conditions experienced by rocks can be evaluated and quantified by using thermodynamic calculations. Time (*t*) is obtained by dating minerals involved in symptomatic parageneses, considered at equilibrium. The resulting *P-T-t* paths are then used to constrain the tectonic history, most of the time, by assuming that the pressure recorded by metamorphic rocks directly depends on burial depth. However, in regions where deformation is large and heterogeneous, like in the Alps, the above assumption is questionable. I will show that the pressure history, including a catastrophic pressure drop at the onset of exhumation, as recorded in most well documented high-pressure metamorphic rocks worldwide (including those from the Alps) fit remarkably well with a two-fold tectonic history, from compressional during subduction to extensional during exhumation.
This contradicts the common assumption that (ultra)high-pressure rocks exhume during continental collision. However, numerous natural examples of (ultra)high-pressure rocks, from early Paleozoic to late Tertiary, document that exhumation occurred in extension either driven by slab rollback prior to continental collision (e.g. in numerous backarc basins) or by eduction, after continental collision (e.g. Norwegian Caledonides). The so-called “Alpine collision” appears to correspond to two successive events of slab rollback leading to the extensional exhumation of (ultra)high-pressure rocks, prior to continental collision.

Widespread Permian granite magmatism in Lower Austroalpine units: Significance for Permian rifting in Eastern Alps

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The Permian tectonic setting of the Alpine orogen remains controversial (i.e., continental rift: Neubauer et al., 2000; Variscan collapse: Ménard &Molnar, 1988, underplating: Schuster &Stüwe, 2008; Paleotethys subduction: Finger &Steyrer, 1990) and is crucial for palinspastic reconstructions of the western Tethys domain during the breakup of Pangea. In this study, we present new U–Pb data for the Permian "Grobgneis" granite, a porphyric orthogneiss (266±19Ma; 272.0±1.8 Ma) of the Raabalpen complex in the Lower Austroalpine unit. A similar Permian granite age (263 ±16 Ma) (Tropper et al., 2007) was reported from Stubenberg metagranite in the same subunit. Locally, the Permian "Grobgneis" is associated with small bodies of undated gabbro. The new geochronological results reveal that the "Grobgneis" of the Lower Austroalpine unit was emplaced during Middle Permian (Guadalupian) times. Some zircons with a very low Th/U ratio zircon in the sample SG3A show Triassic age (ca. 230 Ma), we interpret it present a late Triassic metamorphic age. In addition, the Rb–Sr ages of white micas from the granite yield cooling ages of 231 Ma, also indicating little metamorphic overprint (Schuster's unpublished data as cited in Tropper et al., 2007), which correspond the second extensional event (Neubauer et al., 2018) in Eastern Alps. Interestingly, the Raabalpen basement is covered by locally thick volcanics and then by of latest Permian and Lower Triassic siliciclastic succession and Middle Triassic dolomites. This suggest an interesting relationship between Middle Triassic granites and volcanics in the basement and the relatively thin cover, and these are tentively interpreted as a rift.

As a whole, Permomesozoic siliciclastic syn-rift sequences spread in overall Eastern Alps (Neubauer et al., 2018), we suggest the Permian magmatism (including granite, pegmatite, gabbro and extrusive equivalents) coeval with the HT/LP metamorphism in the Eastern Alps were formed at the onset of lithospheric extension associated with initial rifting of the Variscan orogen during Pangea breakup, the following Middle Triassic tectonothermal event heralding the opening of the Meliata Ocean.

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Heterogeneous structural and metamorphic record in the Zermatt-Saas ophiolite, Valtournanche, Western Alps

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Structural and geological mapping in upper Valtournanche reveal that rock of the Zermatt-Saas Zone ophiolite tectonic unit may record up to four ductile deformation stages (D1, D2, D3, and D4). D1 comprises a foliation and rare vestigial rootless folds; D2 and D3 stages produced almost coaxial folding with shallower and steeper axial plane and foliations, respectively. Finally D4 produced upright open folding with faint local foliation. D2 is also responsible for dominant foliation at the regional scale, recorded in all rock types that comprise the metamorphic equivalents of a complete oceanic lithosphere. In metabasites and carbonatic metapelites, D2 structures testify a subduction-related Pmax corresponding with depths of about 80 km, under a thermal state compatible with a cold subduction, achieved between the Palaeocene and Eocene. The lithostratigraphic setting was mainly structured under these HP conditions where hundred metre-sized gabbro bodies were disrupted into dispersed tectonic fragments along S2 strike. Afterwards, exhumation took place under a thermal state compatible with continental collision. In metabasites and carbonatic metapelites, PT estimates inferred from mineral assemblages marking pre-D2 relict structures indicate a prograde evolution related to burial during subduction; this is in contrast with pre-D2 relicts in serpentinite whose PT estimates indicate a decompression evolution and point to a new UHP pressure peak recorded in serpentinites. These differences indicate that the Zermatt-Saas Zone is composed of heterogeneous tectonometamorphic relicts that were amalgamated during the development of the regional S2 foliation into the Alpine subduction system.

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