Abstract Volume
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01. Structural Geology, Tectonics and Geodynamics

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*Swiss Society of Mineralogy and Petrology (SSMP)*

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1.1
The role of sheet-silicates in the formation of spaced cleavages under changing physico-chemical conditions

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In this study, we investigate the microstructures and geochemistry of slate samples from the Infrahelvetic Flysch units in the Glarus Alps (Switzerland). Samples within this paleo-accretionary wedge show metamorphic peak temperatures from 200 to 320 °C, with increasing metamorphism from the North Helvetic Flysch units, close to the village Weesen towards the Ultrahelvetic Flysch units around Segnesspass, the latter in the close vicinity of the Glarus thrust. Along this metamorphic gradient substantial dehydration takes place, which is linked to specific physico-chemical changes in sheet-silicates resulting in the formation of a spaced cleavage. Different stages in the evolution of the spaced cleavage are now imaged with high-resolution SEM imaging and quantified with Auto-Correlation Function (ACF). The ACF shows that: (1) the microlithon size; (2) the elongation of the microlithons; as well as (3) the far field correlations (overall schistosity) are increasing with metamorphic grade. At the grain scale, the macroscopic cleavage is defined by SPO (shape preferred orientation) of sheet silicates combined by shape changes of large minerals (mainly calcite and quartz) due to pressure solution or viscous deformation processes (diffusion and dissolution-precipitation creep). Phase segmentation of the high-resolution SEM images shows: (1) mica aggregates (about 30 µm) are often deformed; (2) relatively large sheet-silicates (sizes of the long axis of about 20-30 µm) are aligned bedding parallel and (3) relatively small sheet-silicates (long axis of 0.8-2 µm) are also aligned bedding parallel and form an interconnected network. The physical conditions of local fluid-mineral equilibria are unravelled by quantitative mineral chemistry of sheet-silicates (i.e. white mica, chlorite). K-Ar measurements of different grain-size fractions from such rocks yield apparent ages, because of inheritance of detrital grains and their incomplete recrystallization even in the small grain size fractions. Interestingly, however, the apparent ages of fine-grain size fractions are younger compared to coarser ones indicating a volumetrically less advanced resetting progress in the course grains in comparison to the fine grains. Hence the combination of quantitative microstructural and geochemical analyses provides new and important insights into the maturation process of slates. Different tools to quantify the amount of resetting (isotopes, mineral chemistry) show a low amount of detrital input in the fine fraction as well as some resetting in the course grain size fractions.
1.2 The Gondwanan margin in West Antarctica: insights from the Triassic metamorphic basement of the Antarctic Peninsula

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We present a study of seven orthogneisses from the Triassic metamorphic basement of the Antarctic Peninsula that combines zircon U-Pb LA-ICP-MS data with isotopic tracing (Hf in zircon and Sr-Nd-Pb in bulk rock) and whole rock geochemistry. Our results address the current debate regarding the allochthonous vs in-situ origin of the Antarctic Peninsula crust, and the configuration of various lithospheric fragments during the disassembly of southern Gondwana and the subsequent assembly of West Antarctica. The rocks analyzed are part of the metamorphic basement, which precludes the collisional event, constituting useful material to study the pre-accretional history of Antarctic Peninsula. In addition, we compare these data from the Peninsula with other domains of West Antarctica such as Thurston Island and in South America, including Patagonia.

West Antarctica is composed of five former fragments of Gondwana, and the Antarctic Peninsula is currently proximal to Patagonia. Prior to Mesozoic break-up, these blocks were located along an active continental margin that was consuming proto-Pacific oceanic lithosphere (e.g. Storey, 1988). Rifting of Gondwana drove block translation and rotations that eventually lead to the assembly of West Antarctica (e.g. Grunow et al. 1987), although the details of these processes are poorly constrained.

The Antarctic Peninsula hosts a Mesozoic-Cenozoic arc that intrudes early Mesozoic and late Paleozoic sedimentary and metamorphic rocks. Early interpretations utilised litho-stratigraphical correlations between Patagonia and the Antarctic Peninsula to suggest that both formed part of the Mesozoic Andean margin (e.g. Suarez, 1976). Later, Vaughan and Storey (2000), mapped a regionally extensive shear zone in Palmer Land, and proposed that the Antarctic Peninsula formed by the collision of an allochthonous arc (Central Domain) with a former Gondwanan block (Eastern Domain). Burton-Johnson and Riley (2015) question the collisional model on reviewing the basis of sedimentary provenance and the isotopic composition of the igneous units.

Zircons of orthogneisses of the metamorphic basement are complex and yield Triassic rims and Paleozoic cores (zircon U-Pb dates; Flowerdew et al., 2006, Riley et al., 2012). Our LA-ICP-MS analyses of zircon rims in the Central Domain yield U-Pb concordia ages spanning between 207.5 ±5.2 and 216.6 ± 2 Ma, and 203.3 ± 0.6 and 223.4 ± 1.8 Ma in the Eastern Domain, which overlap. However, the ages of the inherited cores are considerably different. The Central Domain records continuous activity until the Late Silurian, with an exceptional age in the Middle Proterozoic. In contrast, the Eastern Domain reveals magmatism during the Triassic, Early Devonian and Late and Early Proterozoic. Evidencing a possible magmatic gap during the Permian-Devonian in the Eastern Domain, that it is present in the Central Domain, suggesting possible different sources for these inherited cores. Furthermore, a comparison of the ages of inherited cores of the orthogneisses with U-Pb provenance studies of the Antarctic Peninsula and Patagonia show that: i) the detritus of Eastern Domain and Patagonia have significant activity gaps while magmatism was occurring in the Central Domain (during the Devonian and Carboniferous); ii) the Eastern Domain show remarkably similarities on the pattern of the inherited cores of its orthogneisses and the detritus of its Triassic sedimentary rocks, suggesting that probably both were nearby prior the Triassic.

Major oxides and trace elements reveal subalkaline, dominantly peraluminous, supra-subduction zone rocks (Pearce et al., 1984), although one orthogneiss of the Central Domain with a concordia zircon U-Pb age of 216.6 ± 2 Ma is metaluminous. The rocks yielded trace element compositions with enriched LILE/HFSE, negative Nb, P and Ti anomalies, flat REE that are characteristic of convergent margins (Pearce et al., 1984).The geochemical data suggest that the protolith of the Triassic metamorphic basement of the Antarctic Peninsula formed in an arc.
Concordant U-Pb data of zircons were used to obtain Hf isotopic compositions. The Eastern Domain yields εHf values of -14.1 to -7.4, while values from the Central Domain span between -13.8 and -3.8. These values are consistent with crustal recycling, showing that from the Proterozoic through the Paleozoic and Triassic the source of the magmas remained consistently crustal.

The Late Triassic ages recorded in the rims of the zircons shows that this metamorphism affected a large section of the Antarctic Peninsula, and that the Central and Eastern domains formed part of the Gondwanan margin. However, these ages acquired from Paleozoic cores suggest that, prior to the Late Triassic, relative to older rocks to the east, and that it was located either further south or north. Paleogeographic reconstructions argue against the possibility of the Central Domain being connected with Patagonia, rendering it more plausible that it was located towards the south.

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1.3
Effects of extensional inheritance on passive margin collapse

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The Wilson Cycle, describing the repeated opening and closing of ocean basins, implies a conversion of passive into active continental margins. However, the buoyancy of the oceanic lithosphere by itself is insufficient to overcome the high strength of the continental margin lithosphere. To lower this bulk strength, the existence of weak zones below the margin has often been speculated. Yet, the conditions of formation of these weak zones have been rarely studied.

Using a high-resolution 3D thermomechanical model – I3ELVIS (Gerya and Yuen, 2003) - of the Wilson Cycle we investigate the formation of the weak zones and their effects on the initiation of subduction at passive margin. For this we use the recent grain-damage rheology (Bercovici and Ricard, 2012) to have a self-consistent model of grain-size evolution in the mantle lithosphere and formation of the related weak-zones.

Results shows that stress concentration in the lithospheric mantle during rifting can induce localized grain-size reduction, which prompts the formation of long-lived weak zones above the lithosphere-asthenosphere boundary. Because this boundary is deflected by the asthenosphere upwelling during rifting, the damage-zones systematically dip away from the ocean. The reactivation of the damaged-zones as reverse zones during convergence allows for subduction initiation at the passive margin. Results show that this subduction mechanism is controlled by the continental Moho temperature. With a high Moho temperature (700°C) the weak zones partially heal through grain coarsening during seafloor-spreading. The resulting ductile strength of the margin is then too high to allow subduction initiation through passive margin collapse. These results show that the thermomechanical conditions of the continental lithosphere at the time of rifting exert a major control on the strength of the passive margin lithosphere and therefore the likeliness to have subduction initiation.

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1.4
Sediment Control on Subduction Plate Speeds

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Tectonic plate velocities predominantly result from a balance between the potential energy change of the subducting slab and viscous dissipation in the mantle, bending lithosphere, and slab-upper plate interface. A range of observations suggest that slabs may be weak, implying a more prominent role for plate interface dissipation than previously thought. The shallow thrust interface is commonly assumed to be weak due to an abundance of fluids and near-lithostatic pore fluid pressures, but little attention has been paid to the influence of the deeper, viscous interface. Here we show that the deep interface viscosity in subduction zones is strongly affected by the relative proportions of sedimentary to mafic rocks that are subducted to depth. Where sediments on the down-going plate are sparse, the deep interface is dominated by mafic lithologies that metamorphose to eclogites, which exhibit viscosities 5-50 times the asthenospheric mantle, and reduce subduction plate speeds. In contrast, where sediments are abundant and subducted to depth, the deep interface viscosity is 1-2 orders of magnitude lower than the asthenospheric mantle, thus allowing significantly faster plate velocities. This correlation between subduction plate speed and deep sediment subduction may help explain dramatic accelerations and decelerations in convergence rates, such as those documented for India-Asia convergence over the Cenozoic.
1.5

Dating retrograde tectonic activity in the Mont Blanc and Aiguilles Rouges massifs dated through ion probe analysis of hydrothermal cleft monazite

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Millimeter-sized hydrothermal monazites from open fissures (clefts) associated with different cleft generations in the Mont Blanc and Aiguilles Rouges massifs have been investigated by ion microprobe (SIMS). The interaction of hydrothermal fluids with the wall rock causes partial dissolution and alteration of the rock. Disequilibrium of the fluid-rock system within the cleft through tectonic activity led to mineral crystallization within the cleft and subsequent stepwise crystal growth. High precision isotope dating yields monazite crystallization ages. Unlike 238U-206Pb ages, 232Th-208Pb hydrothermal monazite ages are not affected by excess Pb and yield a higher precision than ages obtained through the U system.

Of the two cleft generations sub-horizontal clefts formed in a compressive phase, while the sub-vertical clefts formed during younger, strike-slip movements along boundaries on both sides of the Mont Blanc massif and Permocarboniferous deposits of the Aiguilles Rouges massif.

The studied crystals show three main growth phases at ca. 11.5 to 10.5 Ma, 9 Ma and 8 to 7 Ma, with relics of an older crystallization phase. This age pattern is interpreted as signifying (re-)crystallization during the start of dextral strike-slip deformation and later phases of activity along the strike-slip fault system.

All of the crystals are porous and complexly-zoned, an indication of dissolution-reprecipitation processes. Comparison of monazite crystallization ages with thermochronometers indicates that the network of vertical shear zones with down-dip lineation in the Mont Blanc massif became strongly overprinted at around 11.5 Ma. The identified deformation phases indicate the external massifs of the Western Alps to not only share a comparable tectonic position within the Alpine arc having also undergone a similar tectonic evolution.
1.6
Rock-matrix versus fracture-controlled fluid pathways in the upper oceanic crust

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Permeable pathways in the upper oceanic crust control the geometry of mid-ocean ridge (MOR) hydrothermal circulation cells and the resulting chemical exchanges between the crust and seawater. Knowledge of the rock-matrix permeability and the fracture permeability along these pathways is required to enable realistic reactive-transport modelling of mass and heat transfers, such as those involved in forming volcanogenic massive sulphide (VMS) deposits at seafloor discharge sites.

To address this issue, we have examined the permeability distributions in the sheeted dike complex (SDC) and overlying lavas of the Semail ophiolite, Oman, as an example of MOR-type upper crust formed by fast spreading. We have distinguished alteration in recharge zones, where precursor basalts have been altered to “spilites” containing chlorite + albite + actinolite, from alteration in discharge zones, characterized by “epidosites” comprised of epidote + quartz + titanite ±Fe-oxides (Gilgen et al., 2016). For each alteration type we have determined the matrix permeabilities of altered lavas and dikes by standard laboratory measurements. We have also mapped fracture networks in each alteration zone and as a function of distance from seafloor faults. For these zones we estimated fracture permeability distributions by stochastic fracture modelling of discrete fracture networks (DFN).

Our results show that pillow stacks have bulk matrix permeabilities of ~ 2x10⁻¹⁶ m² where spilitised and ~ 5x10⁻¹⁶ m² where epidotised, whereas sheeted dikes have average matrix permeabilities of ~ 2x10⁻¹⁹ m² where spilitised and ~ 3x10⁻¹⁷ m² where epidotised. Fracture permeability is most prominent along normal faults, which are spaced at kilometre-scale in most of the ophiolite. The faults are bordered on each side by damage zones ~ 100 m wide, with fracture frequencies of ~ 0.001 m⁻³ and fractures lengths ≤ 50 m (Fig. 1). Within these fault-proximal zones, connected fracture networks make an appreciable contribution to the bulk permeability. Outside of the damage zones fractures frequency decreases to ~ 0.0002 m⁻³ and fractures are shorter (0.5–20 m). Thus, fractures in the fault-distal zones are rarely connected and hence they do not constitute a permeable network. The distal zones are nevertheless pervasively altered, demonstrating that matrix permeability is the dominant fluid pathway in these zones. At the outcrop-scale, flow leading to either pervasive spilitisation or epidotisation follows rock-matrix pathways that are largely inherited from precursor igneous textures.

Spilitisation reduces the porosity and permeability of precursor basalts, whereas epidotisation enhances porosity and permeability. In the cores and rims of pillow lavas, epidotisation increases the connected porosity by 9–17 vol.% and increases permeability by up to 3 orders of magnitude (reaching 3x10⁻¹⁵ m²). In the SDC, porosity increases by 9–14 vol.% and permeability increases by up to 2.5 orders of magnitude (reaching 4x10⁻¹⁵ m²). Therefore, as well as creating a significantly permeable pathway, epidotisation enables self-propagation of fluid flow without the need for fracture networks. Although epidosites represent segments of fluid upflow zones, in the Semail ophiolite they do not occur preferentially along faults that focus flow towards the known VMS deposits. Instead, discharge of the fluid that forms epidosites may occur diffusely over large areas of the seafloor at some distance from black-smoker-type vents.
Figure 1. Discrete fracture network models surrounding a major seafloor fault, show distinct proximal and distal connectivities (DFN’s pertain to three zones: proximal epidosite, distal epidosite and distal splite). Only fractures that connect to at least one other fracture are displayed, which in the distal zones is a negligible fraction of the total individual fractures (average DFN contains 84000).

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1.7

The Alpine cycle: Modelling orogenic wedge formation from generation of hyper-extended passive margins and forced subduction to continent-continent collision

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The concept of orogenic wedges has been applied to explain the geodynamic evolution of many orogens worldwide. Recent numerical modelling studies have investigated orogenic wedge formation in a shortening lithosphere which was initially homogeneous, that is, having initially a constant crustal thickness. However, many orogens, such as the Western Alps, are characterised by the collision of hyper-extended passive margins which exhibited a significant variation of crustal thickness from the onset of subduction. Also, the pre-Alpine Liguria-Piemonte basin likely lacked a significant amount of newly formed oceanic lithosphere and consisted mainly of inherited and impregnated subcontinental mantle exhumed to the seafloor until embryonic ocean formation.

We perform high resolution 2D thermo-mechanical lithospheric scale numerical simulations to study the dynamics of the Alpine cycle. Modelling of this cycle is subdivided into the following stages: (I) in a slow spreading rift system, a ~400 km wide basin which contains exhumed lithospheric mantle and is bounded by regions of hyper-extended continental crust is generated. (II) the self-consistently modelled hyper-extended passive margin system is thermally relaxed. During this stage, the lithosphere is neither compressed nor extended. No spontaneous subduction initiation due to the densification of the cooling exhumed mantle occurs in the models. After thermal relaxation, (III) the evolved system is shortened and a one-sided, forced subduction is initiated within the proximal part of the passive margin without prescribing any weak zone. (IV) the basin is closed and an orogenic wedge forms during continent-continent collision.

First, we quantify the impact of the initial geometric configuration from the onset of rifting by varying the mechanical strength of the crust, being either an alternating sequence of horizontal mechanically strong and weak layers, or a non-layered, homogeneous strong crust. Second, we vary the duration of the thermal relaxation period to investigate the effect of distinct thermal structures of the basin from the onset of convergence on subduction initiation and orogenic wedge formation. Third, we examine the control of the lithospheric mantle strength on the evolution of the full Alpine cycle by using either dry or wet olivine flow law parameters for the mantle lithosphere and asthenosphere. In cases of low viscosities in the mantle, small density contrasts along the lithosphere-asthenosphere boundary might induce Rayleigh-Taylor instabilities. To ensure that the algorithm accurately resolves such instabilities, we first perform a benchmark simulation for large scale thermal convection. Fourth, we use a parameterisation for serpentinisation of the exhumed mantle lithosphere by replacing the olivine rheology of the top 7 km in the evolved basin by an antigorite rheology at the end of the cooling period. Fifth, we focus on the dynamics within the evolving orogenic wedge investigating the flow field of the crustal material and pressure variations within the wedge.

Potential applications of the model results to the Western Alpine orogeny are discussed.
1.8 Review of Alpine denudation rates from detrital $^{10}$Be concentrations

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Within the past decade, many studies have reported catchment-wide denudation rates for the European Alps based on in situ $^{10}$Be concentrations measured in river sediments. One of these pioneering contributions was conducted along a north-south traverse through the Central Alps of Switzerland (Wittmann et al., 2007) and revealed an apparent correlation between $^{10}$Be-inferred denudation and surface uplift rates. Here we report a compilation of >350 denudation rate data that now allows discussing how denudation rates vary from west to east across the European Alps.

The reported compilation yields a dense and original picture of the denudation rates for Alpine watersheds covering tens-to-thousands square kilometers and integrating the last 0.1-10 ka. We use this compilation to assess how $^{10}$Be-inferred denudation rates distribute with respect to landscape properties (i.e. topographic metrics), environmental conditions (i.e. climate or hydrology) and geodetic settings (i.e. surface uplift) across the entire orogen, with the aim to identify the respective contributions of internal (tectonic) vs. external (climatic) drivers to the recent erosion history of the European Alps.

Our results show that although $^{10}$Be-inferred denudation rates are scattered at small scale (especially in the Central Alps), consistent patterns are emerging when considering the Alps as a whole. In general, $^{10}$Be-inferred denudation rates scale with topographic metrics such as basins’ mean-elevation, slope gradient and relief; but interestingly they are independent of both intensity and distribution of precipitation and/or water runoff (proxies for modern climate). Because the rates of denudation in the Alps do correlate with metrics extracted from the Alpine topography, we infer a partial control related to the late-Pleistocene climatic and erosive conditions (landscape memory). In addition, we find a close relationship between denudation rates and surface uplift in our dataset, confirming previous observations at smaller-scale. We finally re-evaluate the isostatic response to recent erosional unloading along a west-east traverse across the Alps. While millennial denudation and instrumental surface uplift balance each other through isostatic compensation in both the Western and Eastern Alps, excess uplift can be observed in the Central Alps. These observations, in agreement with independent geophysical/geomorphological evidence in the Alps, further suggest that deep-crustal mechanisms (e.g. related to the geometry of the subducted European slab) also contribute as internal forces to the processes of denudation and rock uplift operating at the surface.

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1.9
Reactivation of Gouge-bearing Faults: an Experimental Insight

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Fault zones in the brittle crust constitute pre-existing weakness zones which can be reactivated depending on their friction, their orientation within the stress field and the stress field magnitude. Analytical approaches to evaluate the potential for fault reactivation are generally based on the assumption that faults are zero-thickness ideal planes characterized by constant friction. However, natural faults are complex structures which typically can host cataclastic fault zones of finite thickness. Here we experimentally investigate the reactivation of gouge-bearing faults at different orientations to the maximum principal stress and compare it with theoretical predictions based on analytical models. We simulate pre-existing faults by conducting triaxial experiments on sandstone cylinders containing a saw-cut, filled with a clay-rich gouge and located at various orientations to the maximum principal stress, ranging from 30° to 80°. The pre-existing faults were axially loaded at strain rates of 3.5*10^-6 s^-1, under a constant confining pressure of 10 MPa. Our results show the reactivation of pre-existing faults when oriented at 30°, 40° and 50° to the maximum principal stress and the formation of a new fracture for fault orientations higher than 50°. Although these observations are in agreement with the fault lock-up predicted by analytical models, the differential stress required for reactivation strongly differs from theoretical predictions. In particular, unfavorable oriented faults appear systematically weaker, especially when a thick gouge layer is present. We infer that the observed weakness relates to the rotation of the stress field within the gouge layer during distributed deformation which precedes unstable fault reactivation, as suggested by microstructural observations. Thus, the assumption of zero-thickness planar fault provides only an upper bound to the stress required for reactivation of misoriented faults, which may result in misleading predictions of fault reactivation.
Thermal softening induced strain localization: from first order features to high resolution lithospheric scale numerical models

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Localization of strain plays a major role during geodynamic processes, such as mountain building, and in particular during the formation of shear zones on all geological scales. In the uppermost part of the lithosphere, that is characterized by low confining pressures, strain localization is controlled by brittle-frictional mechanisms. Strain localization is possible at higher confining pressures too, where brittle fracture is unlikely. At these high confining pressures, strain localization in quasi-homogenous domains requires a softening mechanism and we consider here thermal softening (i.e. shear heating), which may be the controlling mechanism of lithospheric scale shear zone formation and subduction initiation.

Thermal softening is a result of the conversion of mechanical work into heat (i.e. shear heating) and of the temperature dependence of rock viscosities. Previous studies have shown that thermal softening can cause strain localization and the formation of large-offset shear zones in ductile materials whose deformation behavior is described with creep flow laws (e.g. dislocation creep). Also, it has been shown that thermal softening induced shear localization can result in significant stress drops of a few hundred MPa.

To quantify shear zone formation by thermal softening we apply three approaches of different complexity, namely (1) dimensional analysis and analytical solutions, (2) numerical simulations with simple flow laws and model configurations but in turn for 1D, 2D and 3D deformations, and (3) high-resolution 2D thermo-mechanical simulations of lithosphere-asthenosphere deformation. Fundamental features of the modelled shear zones are that (i) they are constantly widening due to heat conduction and (ii) that their finite strain variation across the shear zone is smaller (almost an order of magnitude) than the associated temperature variation. We show the general applicability of these features, which have been studied with 1D simple-shear models, by comparing the 1D simple-shear results with results of 2D and 3D shear zone development under pure shear. Finally, we compare the results of the 1D simple shear zone model with results of high-resolution 2D numerical simulations of lithospheric shortening and subduction. In these simulations, we first model the formation of hyper-extended passive margins and mantle exhumation by extending a continental lithosphere. After a period of thermal relaxation, we start to compress the extended configuration, which leads to subduction initiation by thermal softening; in agreement with results of the 1D, 2D and 3D models performed for simpler rheologies and configurations.
1.11
Fast exhumation in early Oligocene and syn-collisional volcanism as revealed by combined FT and U-Pb analysis of detrital zircons in the Central Alps

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Detrital zircon fission-track analysis (DZFT) from syn-orogenic sediments provide a powerful tool to examine the exhumation history of orogenic belts. In addition, U-Pb age dating (LA-ICP-MS) of detrital zircon is helpful in provenance analysis, especially for documenting syn-sedimentary volcaniclastic influx. Both methods are used together to determine the short-term collisional evolution of the Central Alpine orogenic belt as reconstructing the Early Oligocene exhumation and understanding the syn-collisional Periadriatic magmatism. Three samples show similar detrital ZFT age populations, with three different peaks: 33-40 Ma (P1, 20%); 72-91 Ma (P2, 30-40%); and 180-203 Ma (P3, 40-50%). However, there are several grains with similar ZFT ages and U-Pb ages in the P1 (undivided), which supposed to be of volcanic origin. Then, the P1 is divided into: 8-14% of volcanic grains (P1-Voclanic), and 6-13% of basement grains (P1-Basement). The data show that the contribution of volcanogenic input from the Periadriatic magmatic complex is significant in the syn-tectonic sediments, which were ignored in previous studies. These volcanic zircons (P1-Voclanic) must be excluded from the exhumation rate evaluation of the basement. The lag times (P1-Basement) show an increasing trend of 8-15 Myr from Middle to Late Eocene in the foreland basin. This average lag time can be translated into a short-term average exhumation rate from 0.4 to 0.7 km/Myr. Compared with undivided P1 peak which indicates a subcritical wedge state, the basement P1 peak shows a transition at 30 Ma from subcritical to supercritical wedge state. The reasons for decreasing exhumation rate may be the declining of Periadriatic fault movement and volcanic activity (major period: 32-30 Ma). The results provide evidence for a short pulse of fast exhumation in the Central Alps during 32 and 30 Ma. This period is seen as a result of rapid surface uplift and syn-collisional volcanism in the Central Alps, which were caused by European slab break-off and mantle upwelling, as well as the amplified activity of Periadriatic fault system.

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1.12

New Thermochronological Constraints on Thrust Activity in the Subalpine Molasse: Implications for the Late Miocene Evolution of the Central Alps

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The sedimentary archives and the tectonic history of foreland basins can be used to resolve the influence of deep-seated processes on mountain building. Due to its well-established history, the northern Molasse Basin of the European Alps is especially suited to constrain the geodynamic evolution of a collisional orogen. Age constraints on the basin’s exhumation history provide a substantial contribution to the understanding of the orogen’s geodynamic development. In this study, we present new thermochronological data from the Subalpine Molasse in the Lake Thun area (Switzerland), which we compare to published data from along the Alps in order to investigate the young exhumation history of the North Alpine foreland.

Based on low-temperature apatite (U-Th-Sm)/He thermochronology, we constrain break-back thrusting in the Subalpine Molasse between 12 Ma and 5 Ma, thus occurring coeval to the main deformation phase in the adjacent Jura fold-and-thrust belt and to the main NW-directed thrusting phase in the Aar Massif. A comparison to similar studies from the Subalpine Molasse of eastern Switzerland and Bavaria (e.g. Ortner et al. 2015; von Hagke et al. 2012) show that this pattern of tectonic activity is, however, not unique to areas which are bordered by External Crystalline Massifs (ECMs; e.g. Aar Massif), but is consistent along the entire front of the Central Alps. This means that regardless of the hinterland’s architecture, which is highly non-cylindrical along the Alpine chain, the foreland experiences major thrusting in the late Miocene and that thrusting in the Subalpine Molasse is through going, i.e. not necessarily spatially and kinematically linked to the extrusion of ECMs. The orogen-scale occurrence of this late Miocene thrusting event though suggests a driving force acting on a large wavelength, i.e. at the crustal scale. The recently promoted rollback model for the Alps (Kissling and Schlunegger 2018; Schlunegger and Kissling 2015) and new findings on the Aar Massif’s uplift and exhumation history (Herwegh et al. 2017) may be used to explain the observations of our study.

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1.13 Constraining deformation phases in the Aar Massif and the Gotthard Nappe (Switzerland) using Th-Pb crystallization ages of fissure monazite-(Ce)

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Hydrothermal monazite-(Ce), (LREE,Th)PO4, is found in alpine fissures and clefts that formed during tectonic movements under peak to retrograde metamorphic conditions. Subsequent tectonic movements lead to a stepwise growth of minerals on the cleft walls (e.g., Mullis, 1996). The age of this growth stages can be estimated by dating growth domains in monazite-(Ce). In the Tauern window, Austria, it was found that cleft monazite-(Ce) crystallized in a temperature range of ~200-300°C (Gnos et al., 2015).

Crystallization ages of fissure monazite-(Ce) were measured using the Th-Pb isotopic system with the great advantage that this isotopic system is not affected by diffusion under cleft conditions (Cherniak et al., 2004) and that monazite-(Ce) is very resistant to radiation damage (e.g. Meldrum et al., 1998). In presence of hydrous fluid, chemical disequilibrium can trigger crystallization or dissolution/reprecipitation of monazite and reset the isotopic system (e.g. Grand’Homme et al., 2016; Seydoux-Guillaume et al., 2002, 2012). Therefore, hydrothermal monazite-(Ce) is able to record several deformation events through multiple growth and dissolution episodes (e.g. Bergemann et al., 2017; Berger et al., 2013).

Th-Pb data of growth domains of monazite-(Ce) grains from the Aar Massif (AM) and the Gotthard Nappe (GN) were acquired at the SwissSIMS facility. Comparison of Th-Pb fissure monazite-(Ce) crystallization ages to existing crystallization and cooling ages (zircon/apatite fission tracks, muscovite/illite ages from fault gouges, ((U-Th)/He ages) showed that early monazite-(Ce) crystallization occurred slightly above or below the zircon fission track closure temperature and the youngest crystallization overlaps with the apatite fission track closure temperature. Monazite-(Ce) also grows at temperatures of muscovite/illite crystallization in fault gouges. Spot ages show that the earliest stage of crystallization recorded by fissure monazite-(Ce) occurred around 20.2 Ma in the GN and about 3 Ma later in the AM, and the latest crystallization event was recorded at 5.1 Ma in the AM. Under monazite crystallization conditions, protracted deformation was recorded over 14 Ma and distinct phases of monazite-(Ce) growth can be linked with deformation events in the AM and GN area. In the GN, two growth domain age ranges comprised between 16-15 Ma and 14-13 Ma were identified to correspond to the Chièra and post-Chièra deformation phases. In this area only horizontal clefts are found whereas in the AM, both horizontal and vertical clefts orientation is present. In the AM, four growth domain age ranges of 15-14 Ma, 12-9.5 Ma, 12-10 Ma and 9-6 Ma respectively, correspond to the Handegg, Oberaar, Pfaffenchopf and Rhone-Simplon deformation phases.

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1.14

3D finite strain quantification and numerical modelling of the transition between viscous folding and thrusting.

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Field observations (Pfiffner, 1993) in the Swiss Alps and 2D numerical studies (Jaquet et al. 2014) have shown that folding and thrusting is strongly controlled by the mechanical stratigraphy of the geological units. The mechanical stratigraphy is defined by the thickness ratio between competent and incompetent units, where incompetent units constitute frequently detachment horizons. Depending on this ratio either thrusting or folding can be initiated during bulk shortening.

To investigate the control of the lateral variation of this mechanical stratigraphy on the transition between thrusting and folding during bulk shortening, we employ a three-dimensional numerical model with a non-linear viscous rheology. Our 3D configuration consists of a stiff viscous layer that is embedded in a weaker viscous matrix. The layer has a pre-existing weak zone to initiate the folding and thrusting on each side of the model domain. We utilize several initial geometries with varying detachment horizon thickness and different angular orientation of the weak zone.

We focus here on the quantification of the 3D deformation and compute the finite strain ellipsoid for different domains of the model. We calculate the Nadai strain, which quantifies the overall accumulated strain, and the Lode's ratio, which quantifies the strain symmetry such as constriction or flattening. Nadai strain and Lode's ratio are utilized to construct so-called Hsu-diagrams (Hsu, 1966) in order to illustrate the three-dimensional finite strain state.

Our results demonstrate that the Nadai strain does not vary significantly between the folding and thrusting domain, however, the thrusting domain shows systematically higher values. The strain symmetry varies significantly between the different configurations. However, the thrusting domain shows more constrictional strain, whereas folding exhibits more flattening strain. Furthermore, the lateral transition between folding and thrusting generates locally a simple shear, or strike-slip, deformation although the bulk deformation of the model domain corresponds to pure shear. Moreover, we present several visualization methods for 3D finite strain calculated in numerical models.

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1.15

Present-day uplift of the European Alps: mechanisms and relative contributions

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Recent measurements of surface vertical displacements of the European Alps show widespread uplift at rates of up to ~2.5 mm/a in the north-western and central Alps and ~1 mm/a across a continuous region from the eastern to the south-western Alps. Such a rock uplift rate pattern is at odds with the horizontal strain rate field, characterized by shortening and crustal thickening in the eastern Alps and very limited deformation in the central and western Alps. Proposed mechanisms of rock uplift rate include isostatic response to the last deglaciation, long-term erosion, detachment of the western Alpine slab, as well as lithospheric and surface deflection due to sub-Alpine asthenospheric convection. Here, we assess prior work and present new estimates of the contributions from such proposed mechanisms. Lithospheric adjustment to deglaciation and erosion may account for the great majority of the observed surface uplift rates in the eastern Alps, which, if correct, suggests that topography due to plate tectonic related horizontal shortening and crustal thickening is reduced by other mechanisms. In the central and western Alps, the lithospheric adjustment to deglaciation and erosion likely accounts for roughly half of the rock uplift rates, which points to a noticeable contribution by mantle-related processes such as detachment of the European slab and/or asthenospheric upwelling. While it is difficult to independently constrain the patterns and magnitude of mantle contributions to ongoing Alpine vertical displacements at present, future AlpArray-related data should provide additional insights to better constrain these processes. Regardless, it is increasingly clear that interactions between tectonics s.l. and surface unloading processes, rather than individual forcings, are required to explain the current Alpine topographic change.
1.16
The Evolution and Distribution of Chemical Heterogeneity in the Earth’s Mantle

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A better understanding of the compositional structure of the Earth’s mantle is needed to place the geochemical record of surface rocks into the context of Earth accretion and evolution. Cosmochemical constraints imply that lower-mantle rocks may be enriched in silicon relative to upper-mantle pyrolite, whereas geophysical observations tend to support whole-mantle convection and mixing. To resolve this discrepancy, it has been suggested that subducted mid-ocean ridge basalts (MORBs) segregate from harzburgites to be accumulated in the mantle transition zone (MTZ) and/or lower mantle. However, the key parameters that control MORB segregation and accumulation remain poorly constrained. Here, we use global-scale 2D thermochemical convection models to investigate the influences of plate and mantle rheology on the evolution and distribution of chemical heterogeneity. In particular, we focus on the accumulation of subducted MORB within a reservoir in the MTZ. Our results show that deep-rooted plumes as well as stagnant slabs deliver MORB to the MTZ to establish a MORB-reservoir. Relatively low viscosities in the MTZ tend to facilitate the segregation of MORB from harzburgite, and accumulation of MORB in the MTZ. In turn, relatively high viscosities in the lower-mantle tend to suppress the accumulation of MORB at the core-mantle boundary, while promoting the entrainment of MORB by plumes and related delivery to the MTZ. Finally, relatively high plate yield stresses tend to sustain the formation of large MORB piles in the deep mantle, but with little or no effect on MORB-enrichment in the MTZ reservoir. For a wide range of parameters, we find a moderate enhancement of MORB in the MTZ (~15% MORB plus ~85% pyrolite) after 4.5 Gyrs model time, a prediction that can be tested using seismic observations. Our results suggest that the MTZ may play an important role in regulating heat and material fluxes through the mantle.
Numerical modelling of lithospheric flexure at subduction zones: investigation of forces involved in the flexure and in melt extraction from the LVZ.

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Petit-spot volcanoes were found fifteen years ago by Japanese researchers at the top of the subducting plate in Japan (Hirano 2006). This discovery is of great significance as it highlights the importance of tectonic processes for the initiation of intraplate volcanism. The location of these small lava flows is unusual and seems to be related to the plate flexure, which may facilitate the extraction of low degree melts from the base of the lithosphere.

The presence of melts (0.1 to 2%) at the base of the lithosphere has been hypothesized previously to explain changes in electric and seismic properties at 70-90 km depth, i.e. within the low velocity zone (LVZ) (Sifré et al., 2014). A critical question is related to the process associated with the extraction of these low degree melts from the LVZ to produce the petit-spot volcanoes observed on the sea floor.

First models suggested that extension associated to plate bending allows large cracks to propagate across the lithosphere promoting the extraction of melts from the base of the lithosphere (Hirano 2006 & Yamamoto 2014). However, the study of petit-spot mantle xenoliths from Japan (Pilet 2016) has demonstrated that low degree melts are not directly extracted to the sea floor but percolate, interact and metamorphize the oceanic lithosphere.

In order to understand the melt extraction process in the region of plate bending, we performed 2D thermo-mechanical numerical simulations of subduction based on the general plate geometry observed in Japan. The aim of the numerical modelling is to determine the distribution of deformation mechanisms and to quantify differential stresses within a bending lithosphere. The numerical model considers viscoelastoplastic deformation, a combination of laboratory-derived flow laws (e.g. diffusion creep, dislocation creep and Peierls creep) and heat transfer. The models are applied to quantify the distribution of stress, strain rate, and viscosity in and around the flexed lithosphere since these quantities likely control the percolation of melt initially stocked at the base of the lithosphere. We considered two subduction end-members, namely forced- and free- subduction scenarios in order to determine their main differences. Furthermore, we quantified the spatial variations of the gravitational potential energy (GPE) during subduction to measure the forces driving subduction.

Initial results show that plate flexure changes the distribution of the deformation mechanism in the flexure zone, between 40 km to 80 km depth. A change of the dominant deformation mechanism in the subducting lithospheric slab was observed about 200 to 300 km away from the trench. The main deformation mechanism evolves from diffusion creep to dislocation creep and then to Peierls creep. These changes are linked to the augmentation of the stresses in the flexure zone. At the base of the lithosphere, diffusion creep is observed within a thin layer (20 km), which becomes even thinner (10 km) as subduction progresses.

The model allows also to calculate the horizontal deviatoric stress which allow to determine regions in compression or in extension. The results show that the horizontal deviatoric stresses at the lithosphere-asthenosphere-boundary vary as function of the subductions scenarios. Further work will be necessary to prove whether or not the associated stress distribution is compatible with the development of porosity waves, a critical process to extract melts in low porosity media.

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P 1.2
Stress in the Alpine foreland – a kinematic and mechanical approach

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The Alpine foreland comprises the wedge-top Molasse Basin and the Jura fold-and-thrust belt. The sedimentary cover is deformed due to the outward propagation of the Alpine orogenic wedge. Deformation roots into a major Triassic evaporitic décollement. In these two areas, a part of the deformation in the sedimentary cover is characterized by conjugate tear faults. Recent studies indicate that some faults could be close to failure. However, few data are available to fully constrain the state of stress of this foreland. The goal of this project is to better understand the present deformation of the Alpine foreland. To do this, we populate the current model of the studied area with mechanical parameters. We use the Optum G2 and SLAMTec softwares that apply the principles of the Limit Analysis. Optum G2 computes the stress and the velocity fields at the initiation of the deformation. SLAMTec models 2D mechanical evolutions of thrust sequences. Combining these static and kinematic approaches enables to generate models of various mechanical scenarios. Based on existing cross-sections, structural map and 3D models in the foreland, we will test various parameters such as the influence of the position and thickness of the décollement, the influence of basement-inherited structures, or the geometry of the known fault systems. We expect that the results will allow explaining the structural state of the Alpine foreland and will give direct information about the current stress field. These data could then be used to assess the risk linked to exploration and exploitation of natural resources.

P 1.3
The Chazuta Thrust, a large-transport thrust in an evaporites-floored basin (Huallaga Basin, Peru): insights from analogue modelling.

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The Huallaga Basin in the Sub-Andean (North Peru) is a foreland basin where deformation involves an evaporites-related décollement. The basin comprises several syntectonic depocenters, one of which is the Biabo Syncline located at the back of the Chazuta Thrust. This thrust is a flat-floored thrust that has accommodated more than 40 km of horizontal displacement. Despite such a large displacement, the hangingwall has remained remarkably intact with little or no internal deformation and has incorporated a large volume of evaporites at its base.

In order to unravel the formation and evolution of the Chazuta Thrust, we conducted a series of analogue physical experiments that tested the role of various parameters (overburden thickness and geometry, occurrence of early folds, erosion of the foldbelt front). The main goal is to investigate a system in which most of the deformation is accommodated in the frontal part of the chain (Chazuta Thrust), whereas deformation of the thrust sheet itself remains minor.

Results from our experimental investigations suggest that the three key parameters that have allowed for such a long-lived, large-slip frontal thrust to operate are (1) the wedge-shaped syntectonic sediments sourced from the hinterland, (2) the presence of the Biabo Syncline that acted as a bulldozer pushing the evaporites forward, forcing distal inflation and (3) the erosion at the front that favoured a farther advance of the frontal thrust, dragging passively large volumes of evaporites with it.
Luminescence dating and landscape evolution of the Himalaya, Nepal

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The 2015 Mw 7.8 Gorkha earthquake in Nepal, which caused widespread devastation and loss of life, reveals some gaps in our understanding of the deformation of the Himalaya. Here we aim to constrain recent - Quaternary - changes in deformation in Nepal, through quantifying exhumation rates using luminescence thermochronometry.

Optically Stimulated Luminescence (OSL)-thermochronometry [Guralnik B. et al., 2015; King G.E. et al., 2016] is a recently developed very-low-temperature thermochronometer, sensitive to temperatures of 30-100°C, based on luminescence dating of quartz and feldspar minerals. It offers the potential for precise constraint of cooling histories over recent timescales, and provides high-resolution cooling histories beyond the range of other thermochronometric systems. Applying this new technique to feldspar extracts of a set of samples from the Nepalese-Himalaya provides insights into the cooling and thus exhumation/erosion history of the Himalayan fold-and-thrust belt, giving a better understanding of the Quaternary dynamics of the Himalayas.

The Himalaya mountain belt is the result of compressional orogeny due to the continental collision between the Indian and the Eurasian tectonic plates. Different shear zones and north-dipping crustal-scale thrusts accommodate this convergence. In this project, the objective is to analyse samples collected across some of the most tectonically significant structures in the Himalayan orogen. This allows us to better define the location of the main faults, which is still debated [Searle M. et al., 2008; Parsons A.J. et al., 2016], and by quantifying exhumation rates on each side of the faults, to assess the long-term deformation across the major thrusts.

Preliminary results from five samples along the Marshyangdi River give a better idea of the location of the Main Central Thrust (MCT), and indicate variations in exhumation rates between the different tectonic structures. Whilst potentially relating to local surface process and/or climatic differences (i.e. fluvial incision rates, glacial erosion), these data could also indicate recent tectonic deformation, potentially implying Quaternary fault reactivation within this region.

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A new technique to construct crustal 3-D Vs models: Implementation of Ray Tracing, Model Parameterization and Inversion

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We develop a new tool in which we use P-to-S converted waves to construct a fully 3-D shear-wave velocity model of the crust. This technique requires a dense seismological network to map the less-studied S-wave velocities.

We implement an accurate ray-propagator which respects Snell's law in 3-D at any interface geometry. First, we employ an existing ray-shooting tool (Knapmeyer 2004) to calculate P-ray geometry in a global velocity model (iasp91) to arrive at the station. Then, starting from the piercing point at the local Moho, we shoot an S-wave to the surface, which is several km away from the station. We therefore adjust the ray parameter to make the corresponding crustal S-waves arrive at the station.

A synthetic precision test with flat Moho and constant crustal velocity shows that the converted waves reach the station within 10 m. Using local velocity structure and complex Moho geometry, the mean distance is about 150 m (median ~ 40 m) from the station.

We parameterize the model grid using square cells in X and Y directions and define its based on the ray coverage map of actual data. For a 20-year dataset at more than 180 stations recording about 300 000 traces, the mesh size is typically 25x25 km. For each layer, we define an S-wave velocity at the top and at the bottom: this allows to accommodate both velocity gradients within and velocity jumps between layers.

The individual velocity profile along each trace is extracted from the 3-D initial model and the velocity model is continuously updated during the inversion process.

We envisage to manage the inversion by the stochastic Neighbourhood Algorithm (Sambridge 1999a), looking at the ensemble of models that sample the good data-fitting regions of a multidimensional parameter space. We plan to test our approach first a 1-layer Vs model and then introduce intra-crustal discontinuities (e.g. Conrad).

Our first focus region is the Central Alps, where a well-defined Moho map (Spada et al. 2013) and a high-resolution P-wave velocity model (Diehl et al. 2009) are available. We plan to extend our study to the entire Alpine domain in frame of the AlpArray project (Hetényi et al. 2018).

Figure 1. Seismic stations used in the Central Alps.
REFERENCES


P 1.6

Linking seismicity with faults: Insights from a new high-resolution earthquake catalog of Switzerland

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The connection of seismicity with geologically or geophysically mapped faults is a prerequisite for a seismotectonic interpretation but crucially depends on the accuracy and precision of hypocentre solutions reported in earthquake catalogues. In most cases, changes in the network configuration, analysis techniques (e.g. seismic phase picking) and location procedures (e.g. seismic velocity models) introduce significant inconsistencies to earthquake catalogues and therefore hamper high-resolution seismotectonic interpretations. A consistent and realistic estimate of location uncertainties is often missing in many catalogues.

To overcome such limitations in the instrumental earthquake catalogue of the Swiss Seismological Service (SED), we applied an iterative relocation procedure to improve seismic velocity models and hypocentre locations in Switzerland. The proposed procedure involves tomographic inversions of P and S waves of about 3700 local earthquakes to solve the coupled hypocentre – velocity structure problem in 1D and 3D. Nonlinear location algorithms are used to derive consistent uncertainty estimates for the entire catalogue. Finally, we apply relative relocation techniques, combined with waveform cross-correlation to resolve the fine structure of seismicity and to resolve the geometry of active faults in the Alps and its foreland. In addition, the comparison of focal depths with the 3D velocity structure derived from the tomographic inversion will help to constrain host lithologies of upper-crustal seismicity.

We focus on the source region of the ML 4.6 Urnerboden earthquake of 2017, located in the Helvetic nappes immediately adjacent to the northernmost outcrops of the crystalline Aar massif because this region is particularly suited for linking seismicity with geologically and geophysically mapped faults. The seismotectonic interpretation considers absolute locations, 3D velocity structure, high-precision relative relocations, focal mechanisms, geological profiles, structural and geomorphological analysis. 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 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 any more. This implies a change from thrusting mode active during the latest stages of Alpine orogeny active during the Miocene towards neotectonic activity dominated by strike-slip mode in the analysed region.
P 1.7
Effect of grain friction on characteristics of seismic cycles in a sheared granular fault gouge

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The stability of mature faults is shown to depend on properties of fault gouge material. The granular fault gouge is created due to frictional processes that take place in fault damage zone, and a direct result of wear and comminution. Grain shape, surface roughness and particle size distribution of gouge material control the dynamics of fault system and can affect the characteristics of seismic cycles. Here we study the effect of micro-scale grain roughness approximated by the inter-particle friction coefficient on the characteristics of seismic cycles using 3-D DEM numerical simulations. We simulate stick-slip dynamics and systematically vary the inter-particle friction coefficient recording hundreds of slip events to perform statistical analyses. We show that the fault gouge stick-slip frictional capacity (macroscopic friction coefficient), dilation and their variability nonlinearly increase with the particle roughness (inter-particle friction coefficient), but then saturates to a plateau value. Our results show that the average recurrence time and its variability decreases with increasing particle roughness. A rougher fault gouge with higher inter-particle friction coefficient shows a more complex nucleation phase during the stick period. The energy budget analysis of system reveals that a fault system with higher grain roughness is capable of storing higher potential energy but releases the stored energy more frequent compared to a smoother fault. Our results in this study are consistent with numerical and experimental works and complete them by a focus on micromechanics of fault damage zone, showing how numerical models and in particular discrete element simulations can help boost our understanding from fault mechanics.
Bedrock structure, postglacial infill and neotectonic fault structures in Lake Constance

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In November 2017, a consortium between Swiss and German research and governmental institutions carried out a 2D multichannel reflection seismic survey on perialpine Lake Constance. The survey revealed new insights into the diverse geometry of the lake basins, their sedimentary infill, the underlying bedrock structure and paleo- and neotectonic fault features. The lines were shot complementary to a reconnaissance survey that was conducted along the main basin (Upper Lake Constance) and Lake Überlingen in 2016 and were extended to the shallower basins of Lower Lake Constance in the east.

The seismic data aims to close gaps between existing onshore seismic data vintages from Switzerland and Germany, to identify and characterize fault structures in Cenozoic and Mesozoic bedrock and to unravel the sedimentary evolution of the overdeepened lake basin, shaped by multiple glaciations. Of special interest are various fault zones across the eastern basins, such as the Hegau-Lake Constance Graben, the Randen, Mindelsee, Schienerberg Fault Zones (Egli et al., 2016), as well as the Roggwil, St. Gallen and Rhine Valley Fault Zone across the main basin (Heuberger et al., 2016). Considering the present off-fault paleoseismic evidence in the peri-alpine region, primary on-fault evidence should be present as well (Kremer et al., 2017; Diehl et al. 2018). However, seismogenic fault structures with clear surface ruptures are scarcely found in Switzerland (Ustaszewski and Pfiffner, 2008).

The seismic investigation of Lake Constance revealed a new N-S striking fault structure, that is robustly imaged on four individual seismic sections in the main lake basin. It offsets Molasse bedrock reflections, extends upwards into overlying glacial- and glacio-lacustrine deposits up to Holocene layers and even displaces the lake floor by approximately 1 m. This displacement is also confirmed by the bathymetric lake map. The new lake seismic dataset will improve our comprehension concerning the activity of complex fault patterns rooting in Molassic and Mesozoic strata in the North Alpine Foreland basin. In addition, the dataset will substantially contribute to our understanding of the glacial overdeepenings and their possible relationship with deep-rooted fault structures.

REFERENCES
Upscaling microstructural analysis: A new approach applied to experimentally deformed calcite aggregates

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When a rock is deformed the energy of deformation must either be stored or dissipated and both the storage and dissipation are achieved through micro-scale adjustments in the rock. Examples of these adjustments would be twinning, crystal defect production, chemical reactions and dynamic recrystallisation. In general microstructural and petrologic studies focus on documenting these small-scale adjustments and relating them to larger scales through continuum assumptions, e.g. thermodynamics and continuum mechanics. Many of the techniques used to capture evidence of the aforementioned microstructural adjustments require an imaging resolution of at least below 1 micron. This is restrictive and therefore evidence of microstructural change is often limited to neighbourhoods of investigation that range from a few hundred microns, up to a few millimetres. This can produce a picture that is filled with lots of small heterogeneities while in fact the rock is deforming in a very homogeneous way at the larger length scale.

Here we revisit an experimental run on Carrara marble by Barnhoorn et al. (2004) to explore the heterogeneities in the rock. The deformation was shown to be diffused at the sample scale but underwent significant microstructural changes during large-strain torsion experiments (Barnhoorn et al., 2004). Here we apply a combination of scanning electron microscopy techniques, spatial statistics and wavelet analysis to understand how and where microstructural adjustments happen. Ultimately we demonstrate that significant microstructural adjustment occurred and that it is systematic throughout the entire sample. The systematic locations of the microstructural changes probably relate to domains where the most work is imposed on the sample. Therefore, despite grain-scale heterogeneities in the starting material the bulk material properties dominate the rocks response to deformation. Furthermore, once deformation induced more local heterogeneities, like grain size differences, this did not effect the larger scale. Our evidence highlights the care that must be taken when relating local microstructural differences to larger scales of interpretation.

REFERENCES
Seismicity in Western Peloponnese and Ionian Islands: A new investigation with a local network

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From July 2016 to May 2017, we investigated the seismicity in Western Peloponnese and the Ionian Islands to study the crustal deformation of the region. We deployed a network composed of 15 temporary stations (Short Period Lennartz 1s) and 9 permanent seismic stations of the Hellenic Unified Seismological Network (HUSN).

We constructed the catalogue using STA/LTA method and auto-picking using PhasePApy python package (Chen and Holland 2016). Next, we applied the matlab tool PSPicker (Baillard et al. 2014) to refine P- and S-wave arrivals detecting 1515 local earthquakes. In order to constrain the 1D optimum local velocity model using the location error minimization technique, we divided the area into 4 regions corresponding to 4 refined 1D velocity models. The relocated events show a complex crustal architecture with seismicity from 2 to 30 km depth. To highlight the kinematics deformation of the region we calculated moment tensor solutions for the major events (i.e. M>3). By combining the focal mechanisms and the (micro)seismic activity we were able to identify key seismogenic structures.

Finally, we present the preliminary results of an ambient noise tomography pointing out the shallow velocities anomalies beneath the Greek Ionian sea.

REFERENCES
P 1.11
Reconstruction of the geodynamic and magmatic evolution of the Somkheto-Karabagh and Pontides Arcs from the Mesozoic to Early Cenozoic across Armenia, Georgia and NE Turkey

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During the Mesozoic and early Cenozoic the southern margin of the Eurasian continent recorded the closure of the northern Neotethys oceanic domain. The Somkheto-Karabagh and Pontides magmatic arcs in current day Armenia, Georgia and NE Turkey attest for subduction, obduction, and micro-plate accretion events ending with Eurasia-Arabia collision and complete closure of Neotethys oceans.

Three main domains are distinguished in the Lesser Caucasus and NE Anatolia (Figure 1), including from South to North: (1) the South Armenian Block and the Tauride-Anatolide Platform (SAB-TAP), Gondwanian-derived continental terranes; (2) the Sevan-Akera and Ankara-Erzincan suture zones (AESAS) distinguished by the northern limit of ophiolite bodies which were thrust onto the SAB-TAP; and (3) the Eurasian margin, represented by the Eastern Pontides and the Somkheto-Karabagh magmatic arcs. These two belts are in continuation with one another along the Eurasian margin. Their formation is due to the north-dipping Tethyan subduction under the southern Eurasian margin followed by collision. The onset of the north-dipping subduction is not well constrained. However, studies conducted in the Caucasus, Georgia and the Pontides reveal coeval calc-alkaline magmatic activity since the Early or Middle Jurassic. Yet, Cenomanian to Santonian ages have been proposed as well.

New observations, radiometric dating, geochemical and isotopic data of magmatic rocks of the Alaverdi district in NE Armenia and the Bolnisi district in SE Georgia (Lesser Caucasus region) complete a comprehensive dataset pertaining to the Eurasian margin from W Azerbaijan, Armenia, Georgia and into NE Turkey. Results obtained range from calc-alkaline to high-K magmatic arc activity during Late Jurassic times (158-148 Ma) in the Alaverdi district and calc-alkaline to shoshonitic magmatic arc activity during Campanian times (83-81 Ma) in the Bolnisi district. This additional insight is key for the unravelling of the evolution of the magmatism occurring there, and subsequently the evolution of subduction dynamics. In light of the implications of their geochemical characteristics, we can constrain the source and petrogenesis of the subduction-related magmatic rocks. Considering the complexity of the regional, structural and magmatic evolution along the southern Eurasian margin, our multi-disciplinary approach allows us to constrain the plate tectonic and geodynamic evolution of the Pontides-Lesser Caucasus segment of the Tethyan belt.

REFERENCES
Figure 1. A, sketch structural map of the Middle East and Lesser Caucasus regions, after Sosson et al. (2016), modified. Position of map B is indicated. B, structural map of the Eastern Pontides, Lesser Caucasus and Greater Caucasus, after Hässig et al. (2013) and Gamkrelidze et al. (2013), modified.
Spatial relation of surface faults and crustal seismicity: a first comparison in the region of Switzerland

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The deformation pattern in active orogens is in general diffuse and distributed, and is expressed by spatially scattered seismicity and fault network. We select two relating datasets in the region encompassing Switzerland and analyse how they compare with each other. The datasets are not complete but are the best datasets currently available which fully cover the investigated area at a uniform scale. The distribution of distances from each earthquake to the nearest fault suggests that about two-thirds of the seismicity occurs near faults, yet about 10% occurs far from known faults. These numbers are stable for various selections of earthquakes and even when considering location uncertainties. Earthquake magnitudes in the catalogue are smaller than what could be expected from faults lengths. This suggests that the deep fracture pattern is more segmented than the superficial one, or mostly partial rupture during earthquakes, and (partly) the impropriety of the scaling law. Statistics on the distances from each fault to the nearest earthquake reveal that all supposedly-active faults in Switzerland have experienced a typically felt (magnitude 2.5 or larger) event, and only one out of six has not done so in the past four decades. Future applications of the presented approach to more complete or comprehensive fault databases may result in revised numbers regarding the connection between deep and superficial fracture patterns, representative of the regional stress regime.

The public and educational message: (1) in the region of Switzerland, earthquakes can happen in areas without known or mapped faults; (2) not all faults produce earthquakes within a human lifetime, but they seem to do so over long times.

Figure 1. Map view of M≥0.5 events in the time window 2002-2017 in the entire study area, with respect to supposedly-active faults (in pale green). Co-ordinates are shown in the Swiss grid in km.

REFERENCES
A seismological study to investigate the volcanic behaviour of the Irazú-Turrialba complex

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The analysis of unique seismic signals in geothermal and hydrothermal systems presents a valuable insight into the characteristic evolution of volcanic processes, event triggering (volcanic or seismic) and sensitivity to local and regional influences.

The Irazú and Turrialba Volcanic Complex (ITVC) marks the end of a 10-volcano sequence in Costa Rica, distinguishable by an abrupt variation in the lineament of this volcanic arc. The ITVC presents a location of two differing physical states, the closed system of Irazú and actively venting open conduit system of Turrialba. This presents a diverse volcanic setting ideal to deploy a temporary 20 station seismic network. Complemented by the permanent network, a detailed study of this hydrothermal region is undertaken, with influences from the tectonic setting analysed. Seismic data are being used to provide an insight into the temporal variations of this volcanic complex.

Specific seismic identifiers attributed to volcanic processes provide important information pertaining to the geometric and dynamic features of the ITVC. The most common and distinguishable volcano seismic signals are Long Period signals, volcano tectonic events and tremors. A classification of these signals is made to distinguish the temporal evolution of fluid migration and possible permeability changes in this active system. We use a cross-correlation approach followed by a differential travel-time grid search associated with back projections, to stack and normalize the seismic signal allowing us to locate emerging signals. From the results, a spatial and temporal analysis of these signals can reveal patterns of magma migration, locations of conduit systems, contact points between volcanic reservoirs and even fluid driven fracturing events (Chouet 1996; Woods et al., 2017).

Volcano seismic signals generated by the Irazú Turrialba Volcanic Complex and recorded by this network establish a temporal and spatial interpretation of the underlying magmatic plumbing system.

REFERENCES
P 1.14

Present-day crustal deformation of the Turkish-Iranian Plateau: insights from kinematic modelling

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Convergence between the Arabian and Eurasian Plates causes crustal deformation that is partly accommodated within the Turkish-Iranian Plateau and Caucasus mountain belts. The Neo-tectonics of the region is a complex combination of active faults, tectonic uplift, Neogene-Quaternary volcanism, sea-level fluctuations and offset drainage networks. The dominant faults are the NW-SE striking eastern segment of the North Anatolian Fault (NAF) and North Tabriz Fault (NTF), both with shallow and diffuse seismicity and dextral strike slip component. Seismic activity is concentrated along these active faults and is often considered, together with fault properties (location, geometry and slip-rates), a proxy to the crustal deformation. To quantitatively evaluate the spatial distribution of ongoing crustal deformation in the study region, we developed a regional kinematic model, built upon geological information (tectonic plate boundary, fault traces and slip-rates), geodetic measurements (GPS measurements), and principal stress directions.

In this contribution, we present the results of the kinematic model for the E-Turkish-NW Iranian Plateau and surrounding areas. Firstly, the slip rates for all mapped faults are estimated and secondly, the regional strain rate fields are evaluated. Inherent uncertainties are associated to both geodetic and geologic measurements and quantitatively accounted for in our kinematic model. The kinematic slip rates of the faults in the region indicate a high active shortening (~11 mm/yr) across the Alborz-Talesh, Bitlis and Greater Caucasus Mountain ranges. High strain rate fields (Log e = -14.4 to -15.4 s^-1) are concentrated in narrow zones along the eastern segment of NAF to NTF in the Turkish-Iranian Plateau, which might be in relative agreement with morphotectonic studies clarifying active faulting in the region as well as the observed seismicity. However, there are various regions of high strain fields that are not located along fault systems, which might indicate unknown or unmapped active faults. Low strain rate fields are observed in the plateau and valley, away from active features as indicated by low seismicity.

P 1.15

High-resolution thermo-mechanical numerical simulations of basement-cover deformation with application to 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, and (4) the rotation of the basement during shearing due to the flexure of the lithosphere in the foreland. The final aim of the simulations is to reconstruct the overthrusting of the Helvetic nappes over the nappes of the infrahelvetic complex.
High-resolution earthquake catalogue and seismic velocity models to image the structure of seismogenic faults zones in the Valais (Switzerland)

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The seismicity in the Valais (southwest Switzerland) mainly distributed north and south of the Rhone-Simplon line (RSL). The seismicity north of the RSL concentrating at Rawil formed an E-W lineament, sub-parallel to the RSL, but offset by 5-10 km to the north. The RSL forms the tectonic boundary between the Penninic and the Helvetic nappes and is characterized by dextral deformation, which continued at least until 3 Ma. The apparent offset between seismicity and the RSL raises the question where current deformation is localized along the EW striking section of the RSL. Focal depths within this lineament, on the other hand, will provide insights to what degree the underlying basement is involved in the brittle deformation.

To study the fault geometries and the long-term spatio-temporal behavior of such seismogenic zones at high-resolution in the Valais, it is crucial to have accurate and precise earthquake locations with consistent uncertainty estimates. However, the current bulletin of the Swiss Seismological Service (SED), spanning 35 years of data, is biased by changing station network geometries over time. This causes varying hypocentre location quality and completeness of earthquake catalogues. Moreover, changing procedures and algorithms used for earthquake location can introduce systematic errors when combined into one single catalogue. Such catalogues are largely inconsistent in terms of location accuracy. Therefore, we establish a high-quality earthquake catalogue by relocating absolute hypocentre locations of the last 35 years with the minimum 1-D model approach for the Valais region. This catalogue is complete and consistent in terms of accuracy. To further increase the precision of hypocentres, the 1-D models and hypocentres are then used as initial value for a regional relative relocation with waveform cross-correlation to resolve the fine-structure of seismicity.

The new catalogue will provide new insights into the seismotectonics of the Valais and allow the detailed comparison of seismicity and geologically mapped faults. From the preliminary results, we find out the focal depth of seismicity lineament at Rawil range from very shallow (~0 km) to 15 km. Regarding the depth of crystalline basement (~10 km), this may suggest part of the basement is involved in the current deformation. However, most likely only limit to the uppermost basement. We also constrain the Vp/Vs ratio through high-quality S phases. The inversion reveals a high Vp/Vs within the first 2.5 km depth, which may indicate the carbonate sedimentary layer. Furthermore, we compare our results to previous studies of the 2014-2017 St-Leonard and 2011 Sierre seismic sequences.
P 1.17
Understanding seaward-concave subduction zones: insights from critical taper theory and forearc seismicity

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Seaward-concave forearcs are characterized by along-strike differences in surface uplift and exhumation, however, the causes and style of such variations are still a matter of debate. Although forearc uplift is generally considered to be linked to plate interface processes, in fact it is unclear which mechanism effectively produces long-term (Ma) vertical displacement and emergence of coasts. In this study we use the Coulomb-wedge model (e.g. Wang & Hu., 2006) to study the proximal forearc of the Peru-Chile and northern Japan subduction zones, two seaward-concave margins characterized by relative subsidence at the curvature hinge, flanked by actively uplifting limbs. The Coulomb-wedge theory postulates that a wedge’s taper angle is the function of the frictional strength of the wedge material and of the basal detachment. Accordingly, along-strike variations of long-term forearc uplift may reflect changes of (i) slab dip angle, (ii) wedge material strength and/or (iii) plate interface friction. Here, we further explore the latter hypothesis by comparing the spatial distribution of interplate friction (inferred from the measured taper) and the pattern of background forearc seismicity (obtained from the ISC global earthquake catalog). We anticipate that high interplate friction would spatially correlate with larger amounts of seismic moment released in the adjacent forearc. Preliminary results for Peru-Chile show a positive correlation of seismic moment and interplate strength, indicating a wedge in equilibrium. Conversely, in northern Japan a complex relationship between long-term deformation and plate-interface processes is deduced. In both margins, however, low values of interplate friction are needed in order to explain the observed geometry.

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P 1.18
Laboratory evidence of viscous heating-induced strain localization

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In this study we aim to investigate the dynamics of thermally activated strain localization of homogenous and isotropic materials with a strongly temperature-dependent rheology. We present results on coupled thermo-mechanical uniaxial compression experiments on glassy polymer samples with prismatic shape at room temperature and at different strain rates.

With an infrared camera we have captured the spatial and temporal superficial temperature variation. Experimental results are validated with a thermo-mechanical numerical model. The experimental results show a localized strong temperature increase due to viscous heating along planar zones that ultimately become fracture planes. This results are then extrapolated for geological relevant conditions where viscous heating can control large scale shear zones.
P 1.19
Understanding variations in the Alpine deformation imprint on the Aar massif’s basement-cover-contact - the case of the Jungfrau-Eiger Mountains (Central Alps, Switzerland)

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The NW rim of the external Aar Massif was exhumed from ~10 km depth to its present position at 4 km elevation above sea level during several Alpine deformation stages. Different models have been proposed for the timing and nature of these exhumation stages over the last decades (e.g. Burkhard, 1988; Herwegh et al., 2017). One key observation is that although field data allows to locally distinguish multiple deformation stages, before and during the Aar Massif’s exhumation, all related structures formed under similar P, T conditions at the NW rim (Mair et al., 2018). This deformation’s peak temperatures ranged between 250 °C and 330 °C and allowed for the tectonic incorporation of brittlely deformed basement gneisses into the Mesozoic sedimentary cover rocks, which reacted in a ductile manner. The incorporated basement wedges had already been recognized early in the 20th century, but so far, their spatial distribution and their significance has not been systematically studied. However, these gneiss wedges are of great importance since they represent fault zone markers and can be used as proxies for the displacement along the faults.

We use them along with stratigraphic data to link the different structural fabrics in the basement and the Mesozoic cover. We do so by updating pre-existing maps, collecting structural data, and producing a 3D model of the basement-cover-contact. Further we retro-deform tectonic cross-sections within a framework suitable for both basement and cover.

This allows us to differentiate 3 phases of deformation at the NW rim: While the first one mainly affected the sedimentary cover rocks (thin skinned tectonics), the latter two deformed basement rocks of the Aar massif as well (thick skinned tectonics). We find, that along the SW-NE strike of the basement-cover-contact, especially the last phase left a localized and heterogeneous deformation imprint. These deformation stages resulted in the exhumation of the rocks in the Jungfrau-Eiger mountains and together with surface erosion, they are credited for today’s spectacular morphological expression.

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Co-location of the downdip end of seismic locking and the continental shelf break.

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In subduction zones, onshore geodesy provides the main data used to map seismic locking on the plate interface. Based on observations at the Cascadia subduction, we propose a new offshore control by establishing a rationale for the co-location of the locking depth and the shelf break, not the coastline as previously proposed. The erosive shelf of a subduction margin results from the combination of continuous uplift and active wave erosion. The long-term uplift is driven by 1) the non-recoverable fraction of interseismic deformation that mimics the pattern of elastic deformation and 2) continental uplift (e.g. isostasy). We combine a wave erosion model with an elastic deformation model to show how the hinge line that marks the transition from interseismic subsidence to uplift pins the location of the shelf break. The width of the shelf is then set by the amount of coastal retreat under wave erosion. A global compilation of subduction zones with well-resolved locking depths confirms our model with shelf breaks lying much closer to the locking depth than coastlines (mean distances landward of the locking depth of 4.7 and 43.1 km respectively). The morphology of a subduction margin integrates thus hundreds of seismic cycles and it can inform seismic coupling stability through time.

Figure 1. An erosive continental shelf requires wave-base erosion and rock uplift. These conditions are met landward of the uplift hinge line set by the combined patterns of interseismic and continental uplift (top). The shelf break is anchored at the hinge line, and the shelf can grow landward by coastal retreat (bottom). The interseismic deformation is controlled by the pattern of locked, transitional, and creeping segments of the megathrust.
P 1.21
Approach for a new seismotectonic model of Switzerland

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In the year 1997, the Swiss Geophysical Commission (SGPK) launched the project “Seismotectonic Atlas of Switzerland” with the goal of a first nationwide inventory of seismotectonic relevant data. In the course of the project, the contribution of the Swiss Seismological Service (SED) focused on the calculation of earthquake focal mechanisms, the identification of stress regimes from stress inversions and possible ways to present the information on digital maps. Another goal of the project was the compilation of a map of active faults within the Swiss Alps from geological field data. The latter task, however, turned out to be challenging due to a lack of field-based evidence for recent fault activity and therefore only a handful of clearly active (i.e. neotectonic) faults could be mapped. Hence, large uncertainties regarding the seismotectonic interpretation remained.

With the advances in earthquake monitoring and processing (e.g. improved data quality, significant densification of the seismic network, improved seismic velocity models, and relative relocation techniques), accuracy and precision of hypocenters improved significantly, so that today, location uncertainties can be narrowed down to the subkilometer scale (e.g. Diehl et al. 2017). In addition, 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. Allenbach et al. 2017; Heuberger et al. 2016; Sommaruga et al. 2012). Furthermore, with swisstopo’s harmonization of geological vector data (GeoCover) 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) in Switzerland provides increasing data volumes, leading to steady improvements of surface deformation estimates in the Alps and its foreland.

In the light of these new developments, the SGPK has launched a follow-up project called “Seismotectonic Model of Switzerland”. In the corresponding pilot study presented here, we try to highlight different aspects and possibilities of seismotectonic interpretation, but also the pitfalls associated with it. Furthermore, we try to establish a strategic roadmap for the development of a future seismotectonic model of Switzerland.

REFERENCES
Neogene exhumation of the Aar Massif controlled by crustal thickening and paleogeography

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We examine the tectonic contribution to the Neogene cooling and exhumation history of the Aar Massif, Swiss Alps. 89 new and 634 published (U–Th–Sm)/He data on zircon, apatite and zircon fission track ages (AFT, ZFT) are shown in map view as well as on massif-perpendicular and massif-parallel sections, illustrating significant changes in the along-strike thermal overprint and cooling age pattern. Although structural relief and exposed metamorphic grade are highest in the central Aar Massif, youngest cooling ages of all studied thermochronology systems are situated in the eastern- and westernmost surface outcrops (Chur and Brig areas), while ages gently increase toward the center of the massif. Elevation normalized AFT, ZHe and ZFT cooling ages in the central Aar Massif (Reuss Valley) are constant, also in massif-perpendicular direction, and do not reflect the significant structural relief recorded at the top basement marker horizon of the Aar Massif. This is in large contrast to the easternmost cross-section (Chur area), where we observe a bell-shaped AFT age distribution with an age minimum that coincides with the hinge of the Aar Massif culmination. Results of a linear inversion method (Fox et al., 2014, Herman and Brandon, 2015) based on all available thermochronology data highlight that maximum exhumation rates initially occurred at the central Aar Massif, then laterally migrated to the east and west between ca. 12 and 6 Ma, and possibly thereafter. This along-strike evolution is best explained by collisional shortening and thickening starting at the southernmost edge of a European continental margin with a convex shape. Such a scenario is in agreement with the observed transition from compressional- to strike-slip-dominated tectonics in the central southern Aar Massif at ca. 12-15 Ma (Rolland et al., 2009) and with the coeval activation of north-vergent crustal ramps at the external massif front (Herwegh et al., 2017).

The youngest AFZ, ZHe and ZFT cooling ages in the Chur and Brig areas correlate with domains of highest recent surface uplift (Schlatter, 2014), suggesting that exhumation in these regions has accelerated since at least 6-8 Ma. Although glacial erosion, deglaciation and ongoing isostatic compensation might explain the overall increase of exhumation rates since ca. 2 Ma, differential exhumation along and across the strike the Aar Massif extends far into pre-glacial times. Our results indicate that compressional tectonics represent the key driving force for the past exhumation and recent surface uplift patterns, while glacial erosion and likely also other climatic effects are of secondary importance.

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P 1.23

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 for a portion of the southern Dora-Maira Massif (western Alps), with the aim of reconstructing its tectono-stratigraphic and tectono-metamorphic architecture.

The southern Dora-Maira Massif is a (ultra)-high pressure ((U)HP) tectonic nappe stack consisting of different continental crust units which underwent (U)HP metamorphism during the Alpine orogenesis. The study area is located immediately south of the world-famous UHP Brossasco-Isasca Unit and exposes, from the lower to the upper structural level, a quartz-eclogitic unit (i.e the Rocca Solei Unit: RSU) and a blueschists-facies unit (i.e. the Dronero-Sampeyre Unit: DSU), relatively poorly known in terms of lithostratigraphy and metamorphic conditions. Such a geological setting, in which a blueshists-facies metamorphic unit overlays eclogitic metamorphic units, is a unique feature in the Internal Cristalline Massifs and the geodynamic processes responsible for its formation are still debated. Moreover, lithologies apparently related to an oceanic setting (already reported by Carraro et al., 1971 and Henry, 1990) are tectonically interposed between the RSU and the DSU, and their origin has not been interpreted yet.

The detailed field, structural and petrographic study, supported by a geological map at 1:10,000 scale with related GIS-database, was carried out in the Valmala area (a right tributary of the Varaita Valley). Here a lithologically heterogeneous unit named as “Valmala Shear Zone” (VSZ) is tectonically sandwiched between the RSU and the DSU.

The VSZ, which is several kilometers long and about 500 meters thick, shows a “block in matrix” structure. In its lower portion, blocks of metabasics, meta-ultrabasics and calchschists, lenticular in shape and up to hundreds of meters in size, are embedded in a matrix dominated by micaschists, locally rich in carbonates. On the contrary, in the upper portion of the VSZ blocks of micro-augen gneisses and minor impure marbles, lenticular to tabular in shape and up to tens of meters wide, are embedded in a matrix of micaschists and paragneisses.

In the DSU, a metasedimentary Polymetamorphic Complex has been recognised basing on the occurrence of relict pre-Alpine porfiroblastic garnet, and distinguished from a Monometamorphic Complex mostly consisting of metavolcanics. Our findings show that the structural setting of the studied sector is the result of five deformational stages (from D1 to D5). The D2 is the most pervasive one, responsible for the development of the regional foliation S2 and for the activation of the tectonic contacts separating the three tectonic units. Both the VSZ and the DSU preserve relics of the peak metamorphic assemblage compatible with the blueschist-facies (Gln + Grt ± Zo in the metabasics; Ctd + Grt ± Gln ± Lws in the micaschists). Preliminary petrologic data on the metapelites from the DSU constrained peak P-T conditions of ca. 470°C, 19 kbar, in the lawsonite-blueschist facies.

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**P 1.24**

**High-resolution imaging of the Ivrea Geophysical Body: A joint seismic and gravity approach**

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The Ivrea geophysical body (IGB) is a piece of Adriatic plate lower lithosphere, detached during the European-African continental collision. Consequently located at upper crustal depths along the inner arc of Western Alps (Italy), its northeastern portion exposes middle to lower-crustal rocks at the surface in the so-called Ivrea-Verbano Zone. This body is characterised by two main geophysical anomalies: high density and high seismic velocity.

We here aim at refining the IGB structural image, combining high quality seismic and gravity data, together with rock density analyses and geological mapping of the area. The most recent results on IGB structure come from local earthquake tomography, providing no higher resolution than 15 km (Solarino et al., 2018, Diehl et al., 2009). To achieve a higher resolution image, we deployed ten broadband seismic stations along a 50 km linear West-East profile crossing the Insubric Line, the Ivrea-Verbano Zone at the level of the Sesia Valley, and two lakes. Teleseismic earthquakes are used to image sharp and broad discontinuities by means of P-to-S receiver function (RF), performing data stacking and migration. First results already begin to delineate the IGB structure and highlight shallow seismic interfaces, presenting eastward deepening and being well located above the Moho discontinuity.

We also collected 180 new gravity measurements, approaching the target 2-D coverage of 1 point every 4 to 9 km². Together with the existing data, these gravity surveys provide constraints on the IGB density distribution. The surface geological map of the area allows us to compute and refine the Bouguer anomaly map, accounting for rock densities observed on the field, which deviate from the typically used value 2.67 g/cm³. We ultimately aim at developing a 3-D gravity model over the whole Ivrea-Verbano area.

Combining high quality data from different datasets allows us to obtain a newly detailed image of the IGB structure and geophysical Moho itself. Seismic and gravity data will be combined to study 1) contour features in terms of velocity and density contrasts and 2) bulk properties in terms of density distribution. The results will also contribute to the development of further projects in the area, such as the deep drilling project DIVE (https://doi.org/10.5194/sd-23-47-2017).

**REFERENCES**


P 1.25

Structural and metamorphic data in the nappes of the Lepontine Dome (Central Alps)

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New structural and published petrological data on the new geological map and cross sections (1:10’000) of the Osogna sheet (Geological Atlas of Switzerland no. 1293, 1:25’000) are critically discussed. The area includes most nappes of the Lepontine Dome, from bottom to top: the lower penninic units of the Leventina, Simano, Adula/Cima-Lunga and Maggia. These nappes derive from the same post-Variscan gneissic crust, this complicates their lithological distinction within the nappe pile.

All lithologies show a sub-horizontal penetrative foliation that dips gently W to the NW and E to the SE due to doming at the megascale and which intensity varies between rock-types. Close to the Insubric Line to the S, the main foliation plunges with a steep angle to the S. On the foliation plane the mineral and stretching lineation dips NW or SE depending on the plane dip direction. Lineation direction averages at $134°\pm15°$ and dips at $14°\pm9°$. The kinematic analysis indicates a top-to-the-NW shearing.

The geological map shows lithological boundaries that are locally incongruent with the tectonic contacts of the published maps. In the southern part of the Lepontine dome the boundary between the Leventina and the Simano gneisses is interpreted as a moderately deformed magmatic contact that limits the allochthonous character of the Simano unit. Folding and re-activation of the magmatic contact occurred at peak metamorphic conditions between 570 and 620 °C and < 0.6 GPa.

The boundary between the Simano and the Adula/Cima-Lunga units is unclear because of internal and lateral lithological variations occurring at different scales. However, the shear zone is visible through a strain gradient recognizable with a bottom to top closing up of folds (from close to isoclinal folds) and a parallelization of the lithological and structural elements.

The boundary between the Adula/Cima Lunga and the Maggia units follows a folded surface at the base of a granodioritic gneissic body (Cocco gneiss) which in the literature is diagnostic for the Maggia nappe. Along this shear zone, syn- to post-mylonitic leucosomes attest partial melting during deformation.

The High Pressure (HP) metamorphism is limited to minor rock volumes of the Adula/Cima Lunga unit and in one eclogite in the Simano unit and PT conditions peak around ~750°C and 2.5 GPa. The later Barrovian metamorphism is associated with incipient partial melting in the lower units and shows PT conditions ranging from ~600 °C and 0.5 GPa in the Leventina unit to ~650°C and 0.7 GPa in the Adula/Cima Lunga unit.

The correlation of these results is fundamental to better understand the thermobarometric evolution patterns of the Lepontine Dome and the formation of tectonic nappes in general.
P 1.26

Archean tectonics and the generation of continental TTG crust in global mantle convection models

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The tectonic mode in the Archean, and when and how continents formed, are two key unresolved questions. Here we investigate these issues using global simulations of Earth evolution from post magma ocean to the present day, including self-consistently calculated production of basaltic oceanic crust and TTG continental crust. We use the code StagYY in a 2D spherical annulus geometry. The mantle starts with a uniform pyrolytic composition and has an initially hot core. Basaltic crust is formed by partial melting of pyrolytic material, while TTG is formed by partial melting of basalt in certain (P,T) windows [Moyen, 2011] in the presence of water. Produced magma is erupted at the surface and intruded into the crust with a ratio that is specified a priori. After an early overturn of post-magma-ocean-formed crust, we find that the tectonic mode was likely neither modern-day plate tectonics nor a rigid lid, but rather, one characterized by abundant mostly intrusive magmatism resulting in a hot, weak, deformable lithosphere – a “Plutonic Squishy lid” (PSL) [Lourenco, 2017]. In this mode, a thick basaltic crust is recycled at its base by eclogite drips plus episodic delamination of depleted lithosphere [Sizova, 2015]. Abundant TTG crust is produced, with a production rate far exceeding typical continental crustal growth curves [Rozel 2017; Jain 2018]. At the same time it can also be destroyed by entrainment in downwellings. These models thus indicate that (i) subduction was not necessary for the production of early continental crust, (ii) intrusive magmatism was dominant during the Archean (as opposed to “heat pipe” extrusive magmatism), and (iii) Archean tectonics was characterised by a weak, hot deformable lithosphere undergoing extensive delamination as well as significant horizontal motion.

REFERENCES
Lithospheric deformation during rifting involves complex interactions between mantle, crust and surface processes. We investigate the interactions of both upper mantle and lithosphere, and of lithosphere and surface processes, using three-dimensional numerical models. We employ a thermomechanical, visco-plastic code that we couple to a surface process model. The latter evolves the surface by linear diffusion and coupling is accomplished through horizontal advection of topography. This model is used to investigate the effects of erosional efficiency and the impact of mantle plume generation. We investigate the use of integrated work metrics as a measure of rift progression.

In the simplest case, extension along one direction and not including plumes, two factors are found to control rift initiation. The timing of rift initiation is primarily determined by the Moho temperature and thus the integrated rheological strength, but surface process efficiency also plays a significant role. Under fixed thermomechanical conditions, timing of initiation of rifting varies by up to 15%, or ca. 1 Myr, depending on surface process efficiency (i.e. diffusivity). Plume impingement localizes extension and strongly accelerates rift initiation, with earlier initiation for larger plumes. Despite the efficient rift localization by plumes, an impact of mass redistribution by surface diffusion on the timing is also observed. Triaxial far-field forcing (slow horizontal convergence in the direction normal to extension) delays relative rift initiation. In this case, spreading of plume material can facilitate secondary delamination around the tips of the propagating central rift zone.

Analysis of the mechanical work in the entire model over time, measured as energy conversion due to viscous deformation (shear heating, or viscous dissipation; including plastic deformation, which is incorporated through an effective viscosity), depicts the long-term differences in model evolution. Output of total work over time follows a common pattern. Plumes and surface-process variations offset these curves relative to each other, and reflect the effect both have on rifting, even if differences are not apparent from model structures alone.
P 1.28
Numerical two-wedge model applied to the Alpine orogeny
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Two prominent phases of deformation characterize the structure and current geometry of the western-central Alps: 1) nappe emplacement and stacking associated with single-vergent, NW-directed thrusting, and 2) backfolding associated with doubly-vergent, SE-directed movement. For the Monte Rosa region, early subduction and delamination of crustal units has been proposed to explain the nappe stack sequences that emplace ophiolite units onto continental crustal units, associated with areas of high-pressure metamorphism. However, the reasons for switching to late-stage backfolding associated with major uplift at lower grade metamorphic conditions is still ambiguous. This change in deformation style of the Alpine orogeny could potentially be explained by the relative weakening of the orogenic, wedge-shaped, lid with respect to the lower wedge in which nappe stacking took place.

We present simple two-dimensional numerical simulations of two-wedge corner flow, which aim to understand the mechanisms that control the large-scale geometries of the Alpine orogeny. The model consists of a lower wedge situated above the subducting European plate and an upper wedge, which represents the orogenic lid. The model is based on incompressible power-law viscous flow. We aim to quantify: 1) the differences between numerical solutions and analytical solutions valid for simple geometries and linear viscous flow, 2) the impact of variable viscosity contrasts between the two wedges, 3) the impact of an evolving deformable interface between the two wedges, and 4) the impact of linear and power-law viscous flow on the results. Moreover, we compare our model results with the current geometry and tectono-metamorphic history of the Monte Rosa region in the Western Alps.

P 1.29
Strain partitioning linked to high-pressure metamorphism in the Monte Rosa metagranitoids
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The Monte Rose nappe consists of pre-Variscan paragneisses, which were intruded by Permian granitic bodies. The current position of the basement complex resides within the collisional Austroalpine-Penninic wedge, and derives originally from the northern European crust. During the Alpine orogeny, the Monte Rosa incurred a high-P imprint interpreted as the subduction of continental material below the overriding Austroalpine units. Within the metagranites this high-P imprint manifests as 10-50 m wide “whiteschist” bodies consisting of chloritoid, talc, phengite and quartz ± kyanite or garnet.

These whiteschist bodies represent pre-Alpine hydrothermally altered areas which consequently underwent high-pressure Alpine metamorphism. Structurally, the metagranites show strong heterogeneity exhibiting various degrees of strain intensity. However, to this date no deformation associated with Alpine high-pressure metamorphism has been observed as all shear zones are characterized by a greenschist-facies overprint.

We present detailed structural maps of strain intensity within the Monte Rosa metagranites of the Verra glacial cirque, upper Ayas valley, North Italy. We aim to investigate the strain intensity and relative timing of deformation surrounding the high-pressure whiteschists, and bordering the contact with the surrounding basement paragneisses. Our results show that the metagranite exhibits strong strain partitioning. A large area of the metagranites are undeformed and show pristine magmatic textures, even preserving original intrusive contacts with country rock paragneisses. The highest strain intensities are present 1) near the intrusion-county rock contact, and 2) surrounding the high-pressure whiteschist lenses.
Microstructures in damage zones of limestone strike-slip fault in Eclépens.

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The La Sarraz fault system is composed of hectometre-scale subvertical striking NW-SE faults on a branch of the Pontarlier fault system N-S crosscutting Jura Fold-and-Thrust Belt. The Mormont Anticline is present at the southeastern termination of the La Sarraz-Mormont fault northern branch and absent on the southwestern side of the fault zone. The Eclépens quarry is located between two major branches of the La Sarraz-Mormont fault zone.

The La Sarraz-Mormont fault plane measures 150 meters long and half of the fault’s damage zone has a width of 8 meters. The damage zone of the fault consists of fractured host rock, non-foliated cataclasite, foliated cataclasite, and fault gouge. Herein we present a preliminary study of the micro deformation observed in nine samples from the damage zone of the fault. One sample from fault plane, two samples from core zone, one sample from foliated cataclasite and one sample from fractured host rock. Thin sections obtained from oriented hand samples and analysed with cathodoluminescence allowed us to develop a hypotheses of the relative chronological sequence of micro deformation processes present.

The luminescence of the minerals surrounding ooids show a circular bright intensity corresponding to an early cementation. Frequently, between the ooids a darker luminescence is present, most probably originating from a posterior reducing environment corresponding to a secondary cementation. Thereafter, frequent pressure dissolution between ooids is detected. The soluble minerals, with the same intensity as the ooids, is not observed in the vicinity of the ooids but rather in the veins. Veins observed in these thin sections are mostly mineral precipitation on mode I openings. This assumption is confirmed by the observation of half-ooids conserved on both side of the veins. The mineral composition of the studied veins, however, show a darker luminescence than the ooids. The darker intensity observed in the veins might be linked to a late overpressure discharge of reduced fluids. Pressure dissolution took place between the matrix and the veins, this is indicated by the stylolites peaks (brighter luminescence) penetrating the veins (darker luminescence).

The observation of the micro tectonic indicators present in these thin sections allowed us to build the relative chronology of an early cementation, followed by crack and seal processes concurrent to a compression, dissolution and re-precipitation of minerals.
Uplift and exhumation history questions Messinian fluvial unconformities within the Alps

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Erosion, uplift and exhumation of the Alps are the most important forces shaping the orogen. Glacial overprint left a major signature on the geomorphology of the valleys. A period of dramatic incision conditions occurred during the dessication of the Mediterranean in the Messinian stage when the sea level was lowered by thousands of meters. Canyons incised deep into the bedrock around the Mediterranean. The Messinian unconformity is seen in many seismic profiles of the Po Plain, the Rhône Valley and the Southern Alps. This led to the conclusion that the unconformities of the overdeepened valleys are Messinian in age (Bini et al. 1978). This view prevails today, and even in the center of the Alps the incision below today’s sea level has been attributed to Messinian river incision (e.g. Bargossi et al. 2010).

We re-evaluated the incision with paleo-geographic maps and estimates of rock uplift that are extracted from exhumation derived from thermochronometric data (Fox et al. 2016) and sediment budget calculations (Kuhlemann 2007). The study is also constrained by borehole data and seismic profiling in Sinnich in the Adige valley and other published valley fill data. From this, we reconstructed the paleo elevation of the Messinian river profiles in the Alps. Rock uplift regionally estimated must be subtracted from the modern position of the “Messinian” unconformity in order to determine its paleo-elevation in the Messinian. Post-Messinian uplift is supported by observations of Pliocene sediments that are warped up at the southern foothills of the Alps and eroded within the Alps.

We found that the restored profiles in the center of the Alps were at a paleo-elevation at or below the minimum estimated Messinian salinity crisis (MSC) sea level. A Messinian age of the unconformities within the Alps can therefore be excluded, unless the estimate of the sea level or rock uplift is not regionally valid. The alternative interpretation for the inner Southern Alpine valleys is that they are glacial in origin. We predict that a longitudinal seismic section would reveal swells that caused lacustrine sedimentation after ice retreat.

REFERENCES
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The Western Afar Margin, Ethiopia: A new and detailed structural interpretation of a developing passive margin

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The Afar Rift in Ethiopia forms the northernmost segment of the East African Rift System (EARS) and represents one of the rare locations where active continental break-up and the formation of a young passive margin can be examined. A key element in the system is the poorly studied Western Afar Margin (WAM) along the western edge of the Afar, which marks a sharp decrease in topography from the Ethiopian Plateau into Afar (Fig. 1). This developing passive margin is marked by a series of marginal grabens associated with dominant antithetic faulting, as well as ongoing seismicity that pose severe risks to the local population (Fig. 1). How the WAM and its marginal grabens were formed, as well as why it is still actively deforming when deformation should have shifted to the rift axes in the Afar remains unclear. In this study we aim to establish the first detailed structural map of the whole margin, which may serve as a base for further efforts to better understand the evolution and associated tectonic mechanisms in the area.

We apply various methods to chart the structures in the study area. Using satellite imagery and digital elevation models (DEM) we have drafted a detailed fault map of the whole WAM (Fig. 1). We observe how the NNW-SSE oriented marginal grabens are bounded by large faults and are arranged in a right-stepping fashion, separated by transfer zones with a high fault density. Faults have generally the same NNW-SSE strike, except for the southernmost part of the WAM (Fig. 1). By examining slope breaks, hanging wall structures, basin geometry and comparing our interpretation with published data, we can also assess the fault vergence and the quality of our interpretation.

Seismicity analysis of two datasets retrieved between 2007-2009 and 2011-2013 provides further insights (Fig. 1). The main rift axes in the Afar are clearly visible, as well as the seismicity along the WAM. Focal mechanisms from e.g. the GCMT project indicate general normal faulting, which is in accordance with the extensional nature of Afar. By plotting earthquakes and focal mechanisms in section, we obtain an impression of fault activity and fault vergence. Section B-B’ shows various aligned earthquakes, indicating dominantly westward dipping faults, one of which may be the eastern boundary fault of the marginal graben (see topography profile). Note however, that our seismicity datasets have a short timespan and may not register all active faults in the area, thus caution is advised when interpreting.

Further efforts will involve fieldwork to verify our interpretation of the major faults in the area. This work will also form the basis for a series of analogue models to test various scenarios for WAM formation and to reveal the dynamic evolution of the study area.
Figure 1. Western Afar Margin (WAM) with fault interpretation (black lines), earthquake location (2 datasets: red and orange dots) and earthquake focal mechanisms (GCMT). Location of the Afar in the East African Rift System. BRZ: Broadly Riffed Zone; EAP: East African Plateau; Southern African Plateau; ER: Ethiopian Rift; ESP: Ethiopian–Somalian plateaux; KR: Kenya Rift; MR: Malawi Rift; SAP: Southern African Plateau; TR: Tanganyika Rift. A-A’ shows the general topography and structure of the WAM. B-B’ depicts topography, locations and focal mechanisms of earthquakes and interpreted faults geometries. Modified after Corti (2009) and Beyene & Abdelsalam (2005).

REFERENCES
A direct comparison of experimental set-ups for simulating extensional tectonics

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Analogue modellers have historically used different experimental machines and materials to investigate a wide variety of tectonic settings. These methods have yielded valuable insights in tectonic processes, but it is often challenging to compare results from different studies directly. We here present a systematic comparision of different experimental methods simulating continental extension.

We use either a rubber base, a foam base, rigid basal plates or conveyor-type basal sheets to deform overlying experimental materials. The rubber and foam base induce distributed deformation, whereas the plate/sheets bases create sharp velocity discontinuities. For each set-up we test brittle-only (sand) and brittle-viscous (sand and silicone) material layering to simulate the brittle upper and ductile lower crust. These different configurations represent specific tectonic settings. In selected set-ups, we add a structural weakness (a so-called "seed") to further localize faulting. We also vary the extension velocity and viscous layer thickness for a specific experimental sub-set. X-ray CT allows for a detailed 3D analysis of internal and external evolution of the experiments.

A strong difference in faulting style develops between brittle-only experiments with a basal plate or sheet compared with foam or rubber base set-ups (Fig. 1). Foam/rubber base experiments develop distributed faulting. In the case of a rubber base strong boundary effects (conjugate strike-slip faults) occur due to lateral contraction of the rubber sheet (Fig. 1e, f). Pre-defined viscous weaknesses generate central grabens, but do not prevent pervasive faulting (Fig. 1a, b, e, f). Basal plate/conveyor plate experiments strongly localize faulting above the velocity discontinuity with little boundary effects at the sidewalls (Fig. 1i, j).

Brittle-viscous experiments have weak brittle-viscous coupling and show mainly deformation along the sidewalls. In our reference experiments, rifts only develop when seeds are used (Fig. 1c, d, g, h, k, l). In contrast to their brittle-only equivalents, our brittle-viscous basal plate/conveyor plate experiments without a seed do, therefore, not localize deformation (Fig. k, l). Yet at high extension rates, coupling between the brittle and viscous layers increases and downbending occurs along the central axis of the experiment (Fig. 1n). Additional experiments with high brittle-to-viscous thickness ratios lead to the formation of a dual rift structure (Fig. 1p). By contrast, high coupling due to fast extension in foam and rubber base models causes wide rifting (Fig. 1m).

Our results clearly illustrate the strong influence of set-ups on analogue experiments, highlighting the importance of 1) selecting the right set-up for a specific tectonic setting and 2) including detailed information on experimental boundary conditions to allow proper comparison with results from other studies.
Figure 1. Schematic summary of experimental results (top views and sections). (a-l) Experiments with reference brittle-to-viscous ratios and reference extension rates (* = plate base only). (m-p) Additional brittle-viscous tests with high extension velocities and/or high brittle-to-viscous ratios.