01. Structural Geology, Tectonics and Geodynamics

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1.1
Numerical modeling of poro-elasto-plastic behavior using graphical processing units (GPUs)

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Biot’s theory (1962) describes the hydro-mechanically coupled physics of fluid-saturated porous rocks. This theory finds many applications in Earth Sciences. A dynamic response of such a system results in the two longitudinal waves and one shear wave. A quasi-static response results in fluid pressure diffusion. Adding plasticity to such a system enables us to model poro-elasto-plastic behavior, for example, associated with fracturing due to fluid injection.

We present a three-dimensional numerical implementation of poro-elastic physics using graphical processing units (Alkhimenkov et al., submitted). Only 95 seconds are needed to run 1000 time steps of a model having $1150^3$ (1.5 billion) grid cells (Figure 1). This implementation can be used to obtain dynamic (wave propagation) and quasi-static (no inertia) results using the same code. Additionally, we present a simulation considering an elasto-plastic medium in two dimensions (Figure 2). Currently, we are adding more physics to the present 3-D code to model poro-elasto-plastic responses due to fluid injection in a porous medium.

Figure 1. A snapshot showing the total solid particle velocity field in a poro-elastic medium (Alkhimenkov et al., submitted). This is a dynamic simulation (wave propagation).
Figure 1. A snapshot showing the solid displacement and the second invariant of the stress tensor. The heterogeneous medium contains shear bands and is elasto-plastic. This is a quasi-static simulation (no inertia).

REFERENCES
Alkhimenkov Y., Khakimova L., Raess L., Quintal B., Podladchikov Y.Y., Numerical modeling of the anisotropic elastodynamic Biot's equations on graphical processing units (GPUs), Journal of Computational Physics, submitted.
1.2 Deformation processes and weakening mechanisms along a sediment-starved subduction megathrust

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The shallow plate interface in subduction zones accommodates both slow slip events and megathrust earthquakes as a function of pressure-temperature conditions, compositional and fluid-pressure heterogeneities, and deformation mechanisms. These heterogeneities control where, and how, strain localises as rocks are entrained and deformed on the plate interface. It is not well understood how mafic volcanic rocks and oceanic sedimentary rocks, which variably occupy the plate interface during subduction, weaken or deform with respect to one another. Due to the contrasting composition and rheology of these rocks, they are likely responsible for a variety of seismic behaviour.

We present results from field, microstructural, and experimental studies of volcanic and mixed volcanic-sedimentary tectonic mélange from the Chugach Complex of southern Alaska. In the Chugach, underplated slices of volcanic and sedimentary rocks were subducted to depths of 10 to 14 km and reached peak metamorphic conditions of 250-300°C during the Jurassic to Early Cretaceous. These slices of the shallow subduction interface shear zone are composed of either purely seafloor volcanic rocks or a tectonic melange of mixed sedimentary and volcanic rocks and are defined by sharp strain gradients in the field.

We document multiple structures in the Chugach that capture the progressive deformation of seafloor basalts with increasing strain. Several generations of fluid injection drive micro-brecciation of pillow basalt, followed by the development of a spaced tectonic foliation (S planes). Ongoing deformation leads to the formation of shear bands (C and C’ planes) that isolate and wrap lenses of relict brecciated basalt and eventually localize into narrow zones of ultracataclasite. Where sediments (chert, mudstone, rare blocks of greywacke) directly overlie pillow basalt, deformation is more distributed and forms a mixed basalt-sediment clast-in-matrix mélange. Stronger, resistant fragments of chert and greywacke form angular, fractured clasts and altered basalt forms elongated, folded clasts; the clasts are wrapped by a sheared, cataclastic matrix that is derived from altered basalt and mudstone. We interpret these results in terms of the relative and absolute strength of the basalt and basalt-derived mélange and possible styles of seismicity.
1.3 Variscan Schlingen folding in the Central Alps

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Many polymetamorphic pre-Mesozoic basement units of the Alpine belt contain kilometre-scaled folds with steeply inclined axial planes and subvertical fold axes. Those amphibolite facies structures are referred to as Schlingen folds and are described for the External Crystalline Massifs, the Austroalpine and Southalpine basements (Fig. 1). They deform the associated late-Ordovician metagranitoids and are cross-cut by late-Carboniferous intrusions. In the center of the Gotthard nappe (Central Swiss Alps) a well-preserved map-scale Schlingen fold (here called Tros-Schlinge) is the result of a combination of shearing and folding under amphibolite facies conditions. Detailed digital field mapping coupled with petrological and structural investigations reveal synkinematic migmatization in the fold hinge. Reconstructed axial trace of the Tros-Schlinge shows minor fold interference with a younger hitherto not reported prealpine deformation event (Vermigel phase). The superimposed Vermigel phase is locally embodied by a low grade foliation and a minor undulation of Schlingen structures. U-Pb dating of zircons separated from Schlingen axial plane parallel leucosomes yield cores that record a protolith age of 450 ± 3 Ma, and rims with a range of dates from 270 to 330 Ma. The main cluster defines an age of 316 ± 4 Ma. We ascribe this late-Carboniferous age to peak metamorphic conditions of the late Variscan Schlingen phase (water fluxed partial melting 650° – 700° C). The widespread Schlingen folding in pre-Mesozoic basement units of the Alps seems to correlate in time and tectonic style with the late-Variscan Iberian oroclines. Together, they may relate to crustal-scaled transpressive mega-shear zones, that particularly affected units south of the Moldanubian zone with pre-existing subvertical anisotropies (e.g. foliations, bandings) within peri-Gondwana terranes.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.pdf}
\caption{Schlingen structures in the Alps. (a) Compilation map of pre-Permian Schlingen structures described in polycyclic metamorphic basement units of the Alpine belt. (b) Simplified block model of a Schlinge showing a vertical fold with a steep fold axis and steep axial plane. Fig. 1a Modified after von Raumer et al. (2013) and Zurbriggen (2015).}
\end{figure}

REFERENCES


1.4 New Tomographic Models for High-Resolution Seismotectonic Interpretations in the Central Alps

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In this study, we present a new 3-D P and S wave velocity model of the upper crust of the Central Alps and their northern foreland. The tomographic model is derived from a high-quality data set of about 60'000 Pg and 30'000 Sg arrival times of local earthquakes, recorded by the exceptionally dense network of seismic stations in this region. The new tomographic models image the Vp and Vs velocity structure of the Central Alps’ upper crust at unprecedented resolution, including small-scale anomalies such as a (i) Permo-Carboniferous trough in the northern foreland, (ii) Subalpine Molasse units below the Alpine front or (iii) crystalline basement units within the Penninic nappes. The external Aar Massif is characterized by low Vp/Vs ratios of about 1.625-1.675 in the depth range of 2-6.5 km, which suggests differences in Vs resulting from metamorphism of the uplifted crustal block or layered anisotropy.

In addition, the new velocity model is used to improve the absolute location accuracy of hypocentres in the Central-Alpine region. In combination with a probabilistic hypocentre inversion procedure, the earthquake bulletin of the Swiss Seismological Service for the period 1984-2020 was consistently relocated in the new velocity model. The joint interpretation of the 3-D velocity structure and relocated seismicity, combined with information from focal mechanisms and geological and geodetic data, allows high-resolution studies of present-day seismotectonic processes within the upper crust of the Central Alps.

We focus our interpretation on the eastern Aar Massif as well as on the Rawil depression, located in-between the outcropping Aar and Aiguilles-Rouges Massifs. Both regions were recently affected by remarkable seismic events. The ML4.6 Urnerboden earthquake of 2017 occurred near the eastern termination of the Aar Massif, while a sequence of about 350 events occurred in the Rawil earthquake lineament north of the Rhone valley between the Sanetschpass and the village of Anzère in November 2019. Both sequences provide unique insights into active faults in the Central Alps and we image systems of sub-vertically oriented strike-slip faults of variable strike, which root in the crystalline basement in both regions. In the case of the Anzère sequence, high-precision earthquake locations and focal mechanisms image a complex faults system, including a constraining bend along an east-west striking strike-slip fault. In summary, our results document the existence of active strike-slip fault systems in the External Crystalline Massifs of the Central Alps in regions of maximum change in uplift rates.
1.5
Transistion from a radial to a 3D buoyancy-driven hydraulic fracture

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Magmatic dikes are a naturally occurring type of fluid-driven fractures (Rivalta et al. 2015) propagating in the lithosphere due to buoyant forces emerging from the density difference between the host material and the injected fluid (more precisely the difference between the gradients of the in-situ minimum stress and the hydrostatic pore-fluid pressure). The form of such buoyant fractures has been extensively studied in the context of magmatic dikes and shows the appearance of a head-tail structure (Rivalta et al. 2015). 2D plane-strain evaluations highlighted the fact that lubrication flow in the tail is driving the growth of the hydrostatic head (Lister & Kerr 1991; Roper & Lister 2005), which has been confirmed by Germanovich et al. (2014) for the 3D finger-like geometry.

We investigate the 3D transition of a radial hydraulic fracture emerging from a point source towards a buoyancy-driven fracture, focussing on the case of a constant injection rate in homogeneous conditions (homogeneous material properties and buoyancy contrast). We use scaling arguments to characterize the transition and the late time buoyant behavior of the fracture and validate the findings with the fully coupled planar 3D hydraulic fracture growth solver PyFrac (Zia & Lecampion 2020).

Our results confirm a characteristic transition time / length scale from a radial to a buoyant fracture depending on a single dimensionless parameter. The same parameter can be used to predict the fractures overrun (maximum breadth / stabilized breadth). A second, very slow transition takes place between the elongated fracture and the late time fully-developed 3D head-tail structure (similar to the solution of Germanovich et al. (2014)). Our simulations support the appearance of a 3D toughness dominated head structure. They also confirm the importance of the viscous tail as the driving mechanism for the dynamics of such a 3D Weertman’s pulse (form of the head). We quantify how and when the transition from a radial to a buoyant fracture takes place, and it’s implications on the late time behavior.

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1.6  
3D geological modelling of the Doldenhorn nappe (external Central Alps, Switzerland): a glance beyond maps and cross sections

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The Aar Massif (external Central Alps, Switzerland) is the largest of the External Crystalline Massifs, which represent the crystalline basement of the former European passive continental margin that was exhumed during the Alpine cycle (Herwegh et al. 2020). The northwestern (NWRN) rim of the massif is overlain by a series of nappes (Wildhorn, Gellihorn, and Doldenhorn nappe; Burkhard 1988; Herwegh and Pfiffner 2005) that comprise the Mesozoic-Cenozoic parutochthonous sedimentary cover, tectonically detached from its substrate. The lowermost of these tectonic units is the Doldenhorn Nappe (DN). It consists of a large-scale recumbent fold with a thin inverted limb of intensively deformed sediments. The sedimentary rocks of the DN were deposited in a small-sized basin, which has been inverted during the compression of the Alpine orogeny (Burkhard 1988). This study presents a large-scale map and 3D geological model of the DN and the underlying western Aar massif based on two-dimensional cartographic and structural data managed with GIS and 3D modelling technology. The model visualizes the current structural position of the DN and the massif as well as the geometric and overprinting relationships of the articulated deformation sequence that shaped the investigated area throughout the Alpine evolution. Here we document that: (i) the DN is a strongly non-cylindrical recumbent fold that progressively pinches out toward the NE; (ii) the axial surface of the DN is moderately to steeply inclined (60-30°) toward the SW; and (iii) the progressive exhumation of the basement units towards the E and thrusting towards the N. Moreover, along NNW-SSE striking geological cross sections, restoration techniques reveal how the DN basin has been exhumed from ~ 12 km (Berger et al. 2020) to its present position at 4km elevation above sea level throughout several Alpine deformation stages. In this context, special emphasis is given to explore the role of inherited structures (e.g., Variscan-Permian and rifting related basement cover structures) on the Alpine deformation and related exhumation processes in 3D. In summary, today’s structural position of the DN is the result of the inversion of a small basin in an early stage of thrusting, which was followed by sub-vertical buoyancy driven exhumation of the Aar massif and subsequent thrust related shortening. All three stages are deeply coupled with an original non-cylindrical shape of the former European passive continental margin.

REFERENCES
1.7
Subsidence or uplift stage? Surface denudation variations of the Otago upland (New Zealand).

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Landscapes are subjected to surface denudation during their complex and non-linear evolution. Yet, tectonic uplift and surface denudation rates are mostly averaged over multi-millennia. In result, temporal fluctuations are often unknown or even neglected. The recent development of the tor exhumation approach (TEA) focuses on the quantification of the latter. It allows the determination of surface lowering rate variations over continuous time frames within the denudational zone. Here we present the exhumation patterns of eight tors (large residual rocks) in three different landscape locations (valley, ridge, off-site) at Otago, New Zealand. The in situ \(^{10}\)Be ages average around 122 ± 12 ka and range from 836 ± 89 ka to 19 ± 2 ka. The exhumation and surface denudation patterns differ among the three locations. The valley commenced denudation around 200 ka with rates of ~0.22 [m ka\(^{-1}\)] to ~0.02 [m ka\(^{-1}\)]. In contrast, the ridge commenced on average about 0.03 [m ka\(^{-1}\)]. The off-site location denuded continuously for ~120 ka at ~0.20 to ~0.05 [m ka\(^{-1}\)]. Based on published tectonic uplift rates for the area, our modelled surface denudation rates would suggest that the off-site and valley locations are in a lowering state (with tendencies to steady-state), while the ridge location is still rising relative to sea level. Yet, are such different tectonic situations reasonable within 20 km\(^2\)?

REFERENCE
1.8
Earthquake swarms activity in the Southern Red Sea, Afar and Gulf of Aden region from 1960 to 2016

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Rifting events periodically occur at divergent plate boundaries, consisting of magmatic intrusions, earthquake swarms, surface faulting and in some cases volcanic eruptions. While earthquake swarms also occur at other types of plate boundaries, those that have been observed in inland rift zones (e.g., in Afar and Iceland) and in a few offshore cases show in most cases an unambiguous relation with magmatic intrusions. These swarms typically last for a few days to a few weeks, and lack a clear mainshock-aftershock decay pattern pointing at an aseismic transient as a driver of the earthquake occurrences.

Here we present a study on earthquake swarms in the southern Red Sea, Afar and Gulf of Aden. We provide the first earthquake swarm catalogue for the region, which we compiled by integrating reexamined global and local earthquake catalogues with historical observations from 1960 to 2016. We find that in several cases in all the three areas, swarms have been re-occupying the same locations every few decades (e.g., in the Bada area in Eritrea and Port Sudan region in the southern Red Sea in 1967 and 1993, and in the western Gulf of Aden in 1979, 1997 and 2010-2012). When possible, we use focal mechanisms from the GCMT catalog to investigate the source parameters of the largest earthquakes to constrain their occurrence seismo-tectonically. The swarms show different degrees of seismic energy, many of them dominated by multiple earthquakes of Mw4 and Mw5, while occasional larger swarms have earthquake reaching Mw6, such as in the southern Afar region (the Serdo and Dobi areas). Of the three areas, Gulf of Aden shows the highest swarm activity and highest seismic energy release, followed by the Afar area and the southern Red Sea. Despite seeing the least amount of activity and lower magnitudes, the southern Red Sea has experienced multiple earthquake swarms and three volcanic eruptions (two of which resulted in new volcanic islands) from 2007 to 2013. The main characteristic of these earthquake swarms indicates they are driven by magmatic activity and suggests the existence of active spreading centers that are more active than previously thought. We show that the three areas have been subject to an almost simultaneous increase of earthquake swarm activity from 2005 to 2014, also evidenced by three rifting episodes. This period was much more active compared to the preceding decades (1960-2005) and might indicate an increase of magma supply in the region.
1.9
A thermo-kinematic model to investigate heat transfer through the nappes of the Lepontine Dome

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Heat transfer during the emplacement of nappes in an orogenic belt is controlled by three processes: advection, diffusion and production of heat. Production is mainly caused by radioactive decay and shear heating. The relative importance of these processes is contentious. Viscosity, velocity and strain rate affect primarily the contribution of advection and shear heating, which can generate a local temperature increase along the thrust surface. In order to evaluate the relative influence of production, diffusion and advection, we performed 2D thermo-kinematic simulations using the finite difference method. The 2D velocity field is prescribed by a kinematic trishear fault model. We investigate the relationship between nappes’ and isogrades’ geometries resulting from simulations characterized by different configurations of the velocity field. We calculate the thermal evolution and peak temperatures in order to compare the numerical results with field and petrological data. We use data from nappes of the Lepontine Dome (Central Alps, Ticino, Switzerland). These nappes show an extremely pervasive mineral and stretching lineation (NW-SE directed) indicating non-coaxial deformation during shearing at similar metamorphic conditions, and metamorphic amphibolite-facies isogrades locally dissecting the tectonic contacts. We compare the numerical results with field and petrological data collected along the Simano and Cima Lunga nappes.

In the field, the alternation of lithotypes is parallel to the nappe boundaries and constant over their whole, kilometer-scale length. The transition from the Simano to the Cima-Lunga nappe is marked by a progressive change in the texture of gneisses, in which the porphyroblasts become more stretched from the bottom to the top, and by the change in the constituent lithotypes. In the studied area, the Simano nappe is formed mainly by metagranitoids and by minor paragneisses. The Cima Lunga nappe is made of metasediments, mainly quartz-rich gneisses intercalated with amphibolite-gneisses, peridotitic lenses and local calcslchists and/or marbles. Finally, the widespread paragneisses frequently contain garnets of different sizes and internal microstructure. Published and own petrological data of these garnet-bearing rocks are used to constrain the numerical simulations. We test multiple tectonic scenarios related to heat transfer during nappe formation, such as: radiogenic heating; additional heat flux at the bottom of the nappes, due to e.g. magmatic underplating or delamination; or shear heating along nappe boundaries. The results show that transport of heat through advection can’t reproduce an inverted metamorphism below the thrust sheet.
1.10
Deep underplating in an erosive subduction margin: implications for interface rheology and continental recycling

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The viscous subduction interface shear zone downdip of the megathrust impacts large-scale subduction processes, including interplate coupling, mass and volatile recycling, and seismic behavior. Deep underplating, evidenced in the geophysical, geodetic, and rock records, preserves information on these processes, with specific implications for subduction interface rheology and continental mass recycling. We characterized deep underplating processes in the Condrey Mountain Schist (CMS, Fig. 1a), a Late Jurassic to Early Cretaceous subduction complex in northern California. The CMS contains voluminous hemipelagic metasediment with m- to km-scale metamafic and metaserpentinitic ultramafic lenses, all at epidote blueschist facies (0.8-1.0 GPa, 450°C). Limited retrogression and 10+ km of exposed structural thickness make the CMS an ideal location for investigating underplating processes.

We combined geochemical and structural data to identify structures responsible for underplating and to fingerprint protolith sources. We identified two major ductile thrust zones which define map-scale drag folds cored by km-scale ultramafic lenses (Fig. 1b). Above, below, and between these thrust zones, 3+ km thrust sheets record distributed deformation in predominantly sedimentary protoliths. Although kinematics within each ductile thrust zone are consistent across heterogeneous lithologies, stretching directions within the two zones are nearly orthogonal to each other. Consistency of structures in each ductile thrust zone suggests assembly of lithologies prior to underplating. Major and trace element geochemistry, however, indicate a suprasubduction zone source for all ultramafic and some mafic lenses (Fig. 1b). We interpret this combination of structure and geochemical data as indicating a) shallow subduction erosion that sourced the suprasubduction zone-affinity lenses, b) assembly and coherent deformation of heterogeneous lithologies during subduction, and c) protracted underplating at depth.

Underplating processes in the CMS have implications for both 1) interface rheology and 2) continental mass recycling. 1) The CMS records distributed deformation across a sediment-dominated, 3+ km thick shear zone despite subducting along a sediment poor, tectonically erosive margin. Periodic strain localization occurred when rheological heterogeneities (i.e., km-scale mafic and ultramafic lenses) were introduced to the interface. This characterization of interface rheology provides insights into the roles of sediment in interplate coupling/decoupling, as well as transient slip and associated seismic behavior. 2) Modern erosive margins with no assumed underplating serve as the primary recycling path for continental material to the deep interior. Estimated losses to Earth’s interior outstrip continental growth rates, inconsistent with craton stability. Using modern sediment supply rates at erosive margins, CMS underplating rates were 7-22 km³/m.y./km, representing significant sediment storage. Global application of similar techniques to determine a characteristic underplating rate at erosive margins may help balance continental material budgets.

Figure 1. a) Simplified geologic map of the Condrey Mountain Schist (CMS, red dot on inset). b) Schematic of up-dip tectonic erosion and down-dip underplating to form the CMS. Cross-section shows extant orientations of lithologies, protolith sources, and structures responsible for schist assembly. Structures were overturned during Neogene doming from primary east-dipping orientation.
1.11 Successive Au mineralizing events in Archean vein networks during prograde amphibolite facies metamorphism revealed by topological investigations coupled to Au-grade distribution

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Stockwork-hosted Precambrian ore deposits are targets for base and precious metals, such as volcanogenic massive sulfides (VMS) or orogenic Au deposits. Precambrian vein-hosted Au deposits are commonly emplaced under greenschist facies conditions, and in some cases superimposed by amphibolite facies metamorphism and deformation that may lead to Au redistribution. The structural characterization of vein networks and the prediction of the metal grade distribution in such contexts are key challenges for mineral exploration and production.

The Cheechoo gold deposit is hosted by an Archean deformed granodioritic to tonalitic intrusion emplaced into wacke in the Eeyou Istchee James Bay (Quebec, Canada) area in the Superior Province (Fontaine et al. 2018), and that underwent several stages of deformation, hydrothermal alteration and formation of Au-bearing veins recrystallized and metamorphosed during prograde amphibolite facies metamorphism. The first veins are quartz-feldspar-diopside (Qtz-Fsp-Di) veins with albite halos, followed by Qtz veins and pegmatites. Chlorite (Chl) veins that correspond to retrogressive chlorite-coated fractures crosscut all previous veins and structures (Fontaine et al. 2018; Turlin et al. 2019).

In a previous study, we argue that high-grade metamorphism and related deformation of the Au-bearing veins do not allow the use of classical geometric approaches to characterize the stockworks (Turlin et al. 2019). Indeed, these approaches are based on the orientation, relative position and shapes of the veins that have been modified by deformation. Accordingly, we demonstrated that in such cases, the topological approach defined by Sanderson and Nixon (2015) based on the connexions between veins that are not modified during metamorphism, is best suited to decipher the stockwork evolution (Turlin et al. 2019). In addition, it allows an estimation of the networks’ connectivity.

In this study, we couple the topological approach described above with a detailed structural analysis and Au grade and veins distributions. Altogether, the results demonstrate a polyphased Au mineralization. The first phase of veining is represented by Qtz-Fsp-Di and Qtz veins that exert a strong control on the mineralization, as shown by the close relationship between the lognormal distribution of Au grade and the density and connectivity of the vein networks. Zones of strong albite alteration that are associated with these veins are characterized by a similar density and topological vein distribution, but the multimodal Au grade distribution is typical of nugget effects. The injection of syn-kinematic Au-bearing pegmatites is initiated after peak metamorphism and they crosscut the previous vein networks and alteration zones. In these pegmatites, the Au grade distribution is also multimodal as shown by local high-grade values that reach up to several g/t, and that we interpret as a result of Au remobilization during pegmatite emplacement.

Accordingly, in this contribution we demonstrate that (i) the network topology is a strong tool that can be used to characterize deformed and metamorphosed vein networks. Moreover, the combination of (ii) Au grade distribution, (iii) topological characterization of successive vein networks and (iv) a structural analysis allows to decipher mineralizing events (metal input and/or remobilization) and predict metal grade distribution in such metamorphosed and polyphased vein-hosted deposits.

REFERENCES
Correlation between Fracture Network Properties and Stress Variations near Shear Zones

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Spatial stress variations have been observed widely within fault damage zones (Faulkner et al. 2006), which can have a significant influence on scientific and industrial endeavors, such as fault strength, reservoir stimulation, geologic CO₂ sequestration and associated induced seismicity. Based on elastic crack theory (Pollard and Segall 1987), we first derive a complete set of analytical solutions for fractures with elastic resistance and frictional properties under both loading and unloading conditions, which is then applied to a 2D multi-layer model with different fracture density. In this model, we quantitatively relate the global stress response to local fracture deformation with emphasis on specific boundary conditions, i.e., constant strain parallel to the fault strike and constant stress in the off-fault direction.

Simulations are performed to investigate the influences of fracture density, fracture stiffness, fracture frictional coefficient, and pore pressure on the stress variations in four scenarios in which the far-field maximum principal stress is applied at an angle (θ) of 10°, 30°, 60° and 80°, respectively, to the fault strike direction. Results show that both the mean stress and differential stress decrease when the far-field θ is less than 45° and that, when the far-field θ is larger than 45°, the mean stress increases and differential stress decreases with fracture density, as shown in Figure 1. For all cases, the angle θ generally approaches to 45° with the increase of fracture density. The decrease in fracture shear stiffness and frictional coefficient and elevated pore pressure can generate larger stress rotations.

Figure 1. Mohr diagrams illustrating the stress rotations with the increase of fracture density in four cases with an angle (θ) of 10°, 30°, 60° and 80°, respectively, that the far-field maximum principal stress make with the fault strike. For all cases, hydrostatic pore pressure is assumed and the far-field stress is set to be limited by the frictional equilibrium (μ = 0.6).

REFERENCES
1.13
Ductile, brittle and hydrothermal overprint of the Aar Massif’s southern rim (Chli Furkahorn, Switzerland)

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In the course of the exit from nuclear and fossil-fuel energy the research of renewable energies, as the deep-seated geothermal energy, gets an increasing importance. The present Master’s thesis is contextualized within the scope of orogenic geothermal systems, Alpine hydrothermal systems and deep-seated geothermal energy using the example of the Alps. The up to now rarely investigated research area of Chli Furkahorn in the Aar Massif’s southern rim allows to hypothesize hydrothermal activity as it is manifested in the nearby Grimsel area. The present Master’s thesis concerns firstly with the geological history in general and secondly with the brittle deformation of the present rocks in particular. In addition to that, characteristics for paleohydrothermal zones are investigated and the very are integrated in the context of the Grimsel’s paleohydrothermal system. To make statements referring to this multi-scale approach from the kilometer’s range to the micrometer’s range was applied. It was produced both geological-structural maps with lineaments and detailed maps of the paleohydrothermal zones. For the purpose of the identification of pore space cements and microstructures thin sections, REM scans and CL scans were consulted. Furthermore, microthermometry and Raman spectroscopy were chosen in order to determine chemical properties and physical conditions of paleofluids. The hydrothermal system Chli Furkahorn is divided into three hydrothermal stockworks: (1) “deep” hydrothermal stockwork A within the ductile regime, (2) a middle hydrothermal stockwork B at the brittle-ductile transition zone, (3) a shallow hydrothermal stockwork C in the brittle field. The “deep” hydrothermal stockwork A implies at least two generations of ductile deformed quartz veins cross-cutting mainly the mylonites of the compressive Handegg phase and moreover mylonites of dextral, transpressive Oberaar phase. Throughout the Handegg phase shear zone bridges or linkage zones are being formed, later on these bridges were reactivated by the Oberaar phase as oblique strike-slip faults. This ductile initiation of the large-scale shear zone pattern does manifest in form of a wedge geometry within the paleohydrothermal zones. These shear zone bridges represent the tectonic pre-conditioning for the future hydrothermal stockworks B and C. Through the incipient cooling as a consequence of uplift of the Aar Massif the ductile wedge was throughout the Oberaar phase brittlely reactivated. This led to fracturing along former ductile shear zones and therefore an increase of the permeability promoting the subvertical ascent of geothermal paleofluids. Hence, there at least two generations of subvertical and subhorizontal ductile-brittle deformed (kfsph-) quartz veins, cross-cutting the aplitic rim facies’ microgranites and apilites as evidences for the hydrothermal stockwork B. Strongly negative anomalies (54 cps) are connected with paleohydrothermal zones, which may attribute to the shallow hydrothermal stockwork C. These negative anomalies are based on the dissolution of radioactive minerals and therefore the “dilution” of the residual rest radioactivity. It exists at least four generations of subhorizontal macrocrystalline quartz veins, cross-cutting the hydrothermal breccias, at least one generation of microcrystalline vein quartz (chalcedony), as well as at least 11 generations of pore space cements. Within the pore space cements K, Si, Mg and Fe phases in terms of silicates and oxides can be identified. In addition to that Ca phases in terms of carbonates, as well as few and far between some S-phases as sulfides do arise in the geological older areas within the shallow hydrothermal stockwork C. In the geological younger areas of the shallow hydrothermal stockwork C Na and Mn phases in terms of carbonates exist. The CO$_2$-NaCl-H$_2$O fluid inclusion assemblages within the geological oldest generation of quartz veins show homogenization pressures of 304 bar and homogenization temperatures of 250 °C, as well as, salinities of 6.5 wt.% NaCl and densities of 0.77 g/cm$^3$. Furthermore, the H$_2$O-NaCl fluid inclusion assemblages arise with homogenization pressures of at least 44 bar and homogenization temperatures of at least 246 °C, as well as, salinities of 6.16 wt.% NaCl and densities of 0.85 g/cm$^3$. Therefore, in terms of the shallow hydrothermal stockwork C it concerns a K-Si-Mg-Fe-Ca-Na-Mn-S-CO$_2$-O$_2$-H$_2$O-NaCl system with at least 18 paleofluid circulations. Within the shallow hydrothermal stockwork C the episodic fracturing is predominating. It exists strongly increased open fracture and matrix porosities in both relictic ductile-brittle quartz veins and the aplitic rim facies’ microgranites and apilites. With increasing brittle strain gradient and with decreasing geological age of the hydrothermal units decreasing open porosities are denoted with values of 2.2 to 12.5 vol.%. At the Chli Furkahorn insights into the deep structure and the chronological evolution of a fault-linked orogenic hydrothermal system is opened up.
1.14
Mapping and modelling a developing magma-rich passive margin: the Western Afar Margin, East Africa

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This multidisciplinary research project (Zwaan et al. 2020, in review) focuses on the tectonics of the Western Afar Margin (WAM), which is situated between the Ethiopian Plateau and Afar Depression in East Africa. The WAM represents a developing passive margin in a highly volcanic setting, thus offering unique opportunities for the study of rifting and (magma-rich) continental break-up so that our results have both regional and global implications.

We show by means of earthquake analysis that the margin is still deforming under a ca. E-W extension regime (a result also obtained by analysis on fault measurements from recent field campaigns), whereas Afar itself undergoes a more SW-NE extension (Zwaan et al. 2020). Together with GPS data, we see Afar currently opening in a rotational fashion. This opening is however a relatively recent and local phenomenon, due to the rotation of the Danakil microcontinent modifying the regional stress field (since 11 Ma). Regional tectonics is otherwise dominated by the rotation of Arabia since 25 Ma and should cause SW-NE (oblique) extension along the WAM. This oblique motion is indeed recorded in the large-scale en echelon fault patterns along the margin, which were reactivated in the current E-W extension regime. We thus have good evidence of a multiphase rotational history of the WAM and Afar.

Furthermore, analysis of the margin’s structural architecture reveals large-scale flexure towards Afar, likely representing the developing seaward-dipping reflectors that are typical for magma-rich margins. Detailed fault mapping and earthquake analysis show that recent faulting is dominantly antithetic (dipping away from the rift), bounding remarkable marginal grabens, although a large but older synthetic escarpment fault system is present as well.

By means of analogue modelling efforts (Zwaan et al. in review) we find that marginal flexure indeed initially develops a large escarpment, whereas the currently active structures only form after significant flexure. Moreover, these models show that marginal grabens do not develop under oblique extension conditions. Instead, the latter model boundary conditions create the large-scale en echelon fault arrangement typical of the WAM. We derive that the recent structures of the margin could have developed only after a shift to local orthogonal extension. These modeling results support the multiphase extension scenario as described above.

Altogether, our findings are highly relevant for our understanding of the structural evolution of (magma-rich) passive margins. Indeed, seismic sections of such margins show very similar structures to those of the WAM. However, the general lack of marginal grabens, which are so obvious along the WAM, can be explained by the fact that most rift systems undergo or have undergone oblique extension, often in multiple phases during which structures from older rifts control subsequent deformation.
Figure 1. Multiphase rotational extension scenario for Afar (Zwaan et al. 2020).

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1.15
Interacting rifts in orthogonal vs. rotational extension experiments: implications for the East African Rift

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During extension of the continental lithosphere, rift basins develop. These are often initially offset, and must interact and connect in order to create a continuous rift system, that may ultimately achieve break-up. When simulating extensional tectonics and rift interaction structures, tectonic modellers often apply a continuous extension rate along the strike of a rift (system). Yet in nature, extension velocity variations occur along rifts and plate boundaries since plates move apart about a pole of rotation. This results in rotational extension, causing rift propagation and structural gradients (Fig. 1). Here we therefore present analogue experiments of rift interaction structures to compare the effects of orthogonal extension versus rotational extension conditions.

Our modelling efforts (Fig. 2) show that rotational extension and orthogonal extension produce significantly different large-scale structures. Rotational extension can cause significant changes in rift maturity between rift segments, delay rift interaction zone development, and make rift segments propagate in opposite directions (both towards and away from the rotation pole). Still local features in a rotational extension system can often be regarded as evolving in an orthogonal extension setting. Furthermore, we find that various degrees of rift underlap produce three basic modes of rift linkage structures. Low underlap distance (high angle φ) experiments develop rift pass structures. With increasing underlap distance (φ = ca. 40°), transfer zone basins develop. High degrees of underlap (φ ≤ 30°) tend to result in en echelon sub-basins. Our results match with data from previous modelling efforts and natural examples. We furthermore propose a large-scale tectonic scenario for the East African Rift System based on the effects of rotational extension and associated rift propagation observed in our models (Fig. 3). These insights may also be applicable when studying other large-scale rift systems (e.g. the South Atlantic).

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Fig. 2. Model results (final top views) of orthogonal- and rotational extension experiments (Zwaan & Schreurs, 2020).

Figure 3. Evolution of the East African Rift System (Zwaan & Schreurs, 2020).
P 1.1
Dynamics of rotational rift systems: imaging, quantification and linkage of deep-seated flow and surface deformation

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Extension gradients in rift settings with a rotational component yield triangular basin structures with a laterally propagating rift tip. Compression-driven pressure gradients on the other side of the rotation axis induce along-strike lower crustal flow, which eventually influences the rift morphology and dynamics close to the rotation axis.

The aim of this study is to quantify dynamically scaled analogue experiments to investigate the influence of tectonic loading on rifting in a rotational setting where a rotation axis separates extensional and compressional domains. We monitor surface and internal deformation and focus on the interaction of surface rift propagation and internal flow. The surface topography evolution (DEM) and deformation (3D displacement field) is monitored and quantified using 3D Digital Image Correlation (3D stereo DIC) techniques and model internal deformation is investigated by digital volume correlation (DVC) techniques applied on X-ray computed tomography data of time-series experiment volumes.

Our models consist of a brittle-viscous setup overlying a foam base that expands and contracts homogeneously while applying extension and compression, respectively. A quartz sand layer represents a brittle upper part of the crust and sits on top of a viscous mixture that simulates a ductile lower part of the crust. An additional sand package on the compressional model part simulates tectonic loading and initiates rift-parallel flow (Fig. 1).

The conducted models show i) sequential rift propagation with transition from bidirectional to unidirectional fault growth in the upper crust, ii) enhanced rift-opposing horizontal flow in the lower crust and iii) a flow related topography close to the tectonic load (Fig. 2). These results highlight the importance of such out-of-plane motions in rift systems and are of great importance for the understanding of dynamics in rotational rift settings.
Figure 2. Conceptual analogue model showing the influence of pressure driven lower-crustal viscous flow on topography due to tectonic loading and indicated rift propagation for a crustal-scale two-layer model.
P 1.2

How different mantle and crustal weakness orientations affect rift systems: insights from 3D analogue models

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During extension of the continental lithosphere, deformation often localizes along pre-existing weaknesses originating from previous tectonic phases. When simulating such structures with analogue or numerical methods, modellers often focus on either crustal or mantle heterogeneities. By contrast, here we present results from 3D analogue models to test the combined effect (and relative impact) of (differently oriented) mantle and crustal weaknesses on rift systems.

Our model set-up involves a rigid base plate fixed to a mobile sidewall (Fig. 1). When this sidewall moves outward, the edge of the base plate induces a “velocity discontinuity” (VD) that acts as an upper mantle fault/shear zone in a strong upper mantle. The VD is either parallel to the model axis, or 30˚ oblique. On top of this base plate, we apply a viscous layer representing the ductile lower crust, followed by a sand cover that simulates the brittle upper crust. Crustal weaknesses were either imposed by implementing “seeds” (i.e. ridges of viscous material at the base of the sand layer), or by pre-cutting the sand. Similar to the basal plate edge, we apply different crustal weakness orientations as well.

Without weaknesses in the model crust, an axis-parallel base plate forms an axis-parallel rift basin above the VD (Fig. 1a). When adding (oblique) seeds, they strongly localize deformation, creating a series of obliquely oriented grabens. Yet the VD still induces faulting along the model axis, leading to the development of offset axial grabens as well (Fig. 1b). Pre-cut faults also localize deformation, but are less dominant than the seeds (Fig. 1c). As a result, the VD has more control and the axial rift structures are much more pronounced. In the oblique base plate case, the reference model develops a series of en echelon grabens along the VD (Fig. 1d). Axis-parallel seeds strongly localize faulting, to such a degree that the effect of the VD is very much overruled (Fig. 1e). Pre-cut faults allow more influence from the VD, but still dominate the system (Fig. 1f). Doubling the extension rate increases the strength of the viscous layer, enhancing coupling between the VD and sand cover, so that a series of en echelon grabens crosscutting the seed-induced structures develop (Fig. 1g). The above assessment is based on top view imagery. Further analysis of horizontal and vertical displacements and computer tomography analysis will provide additional insights in both internal and external model evolution (Fig. 2e-f).

So far we find that the orientation and relative weakness of inheritances in the mantle and crust, as well as extension rates control subsequent rift structures. These structures can be complex due to the interplay of the above factors, and importantly, all develop under the same pure shear extensional boundary condition. Our results show that very differently oriented rift structures can form during one phase of extension without the need to invoke multiple rift phases.
Figure 1. (a-c) Top view results of models with an axis-parallel base plate (yellow). (d-g) Top view results of models with an oblique base plate (yellow). (e-f) CT-scan results from EXP854 (rerun of EXP834).
P 1.3
Faulting and magma propagation interactions during volcano-tectonic events (Iceland): insights from structural data and analogue modelling.

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Volcano-tectonic events are found in various geological settings, included extensional environments. Understanding how magma propagates in the crust and eventually where it will erupt is one of the key challenges in volcanology research. Classical models of magma propagation assume Earth’s upper crust as homogeneous and fully elastic and they do not account for pre-fractured medium. However, in volcano-tectonically active systems, inherited structures exist and may not be optimally oriented with the current stress field.

This study analyses the role of pre-existing crustal structure and their reactivation on the propagation of magma in extensional environments.

Iceland counts several recent rifting episodes in its volcanic systems, which involve reactivation of pre-existing structures. Literature on the Icelandic rifting events and their return periods suggest a cyclic nature of strain deficit loading and subsequent release. These cycles at divergent plates boundaries are expressed as a steady ~2 cm/yr average extension rate in the far-field and as discrete, stepwise opening in the near-field.

Based on the strain deficit concept, we mapped representative structures in the North Volcanic Zone with a fixed-wing UAV. We surveyed the areas of Fjallagjá, Kollöttadyngja, Eggert, the 2014 landslide in Askja caldera, the monocline in Grióttagjá, and Námafjall.

The processing of the drone images resulted in a DEM (2-3 cm/px) and an orthomosaic (1-2 cm/px) of the fieldwork area. On this imagery, we performed a detailed morphological and structural analysis, looking at the shape of the overall graben structures and the effect of the topography on the faulting processes. Results highlight oblique interactions between two main sets of orientations: the main one, N-S, and a younger one, NE-SW. We will further look at fractures and potential kinematic indicators to reconstruct the paleostress history of this area of the plate boundary.

Parallel and based on the results of the field observations, we are building up an analogue experiment setup. The experiments will include extension, representing the long-term tectonic deformation, and injection tests, representing the short-term magmatic intrusions, to analyse the role of the structure’s presence and reactivation during magma propagation.
The formation of alkaline magmas observed worldwide requires that low degree-melts, potentially formed in the asthenosphere, were able to cross the overlying lithosphere. Fracturing in the upper, brittle part of the lithosphere may help to extract such melts to the surface. However, the mechanism of melt migration in the lower, ductile part of the lithosphere is still contentious. Metasomatic enrichment of the lithospheric mantle demonstrates that such low-degree melts interact with the lithosphere, but the details of this interaction remain unclear. The aim of this study is to better understand the migration of melt in a porous medium at pressure (P) and temperature (T) conditions relevant for the base of the lithosphere and underlying asthenosphere. We investigate melt migration numerically with a newly-developed Thermo-Hydro-Chemical model of reactive transport using thermodynamic data obtained via Gibbs energy minimisation. We perform Gibbs energy minimisation with a self-developed MATLAB algorithm using a linear programming algorithm. We consider, first, a simple ternary system composition of MgO, FeO and SiO$_2$ based on the olivine phase diagram system, Forsterite (Mg$_2$SiO$_4$) – Fayalite (Fe$_2$SiO$_4$). The initial results show that at the employed P and T conditions, if we only use the olivine system, the melt density is larger than the solid density and the melt would sink downward. To reverse this effect, we extend the system by adding more SiO$_2$ using experimental data from Davis et al. (2011). The ternary system of MgO, FeO and SiO$_2$ mimics simple mantle rocks consisting of olivine and pyroxene for which the melt density is smaller than the solid density. All model variables (density, energy, chemical composition of the melt and the solid) are a function of T, P and chemical composition of the system (C). These variables are computed in both the thermodynamic data and in the reactive transport code, and can therefore evolve freely. This allows to quantify the impact of variations in the chemical composition on the migration velocity of the melt.

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P 1.5

Subduction channel vs. orogenic wedge model: numerical simulations, impact of serpentinites and application to the Alps

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The European Alpine orogen results from the closure of the Piemont-Liguria ocean and the subsequent collision of the Adriatic and European plate. Whether the Piemont-Liguria ocean was floored by significant volumes of a mature, 8-km thick Penrose-type oceanic crust, or only by minor volumes of embryonic oceanic crust is still subject to debate. Also, the plate tectonic processes leading to the formation of orogens, such as the European Alps, are often embedded in long-term (>150 Myrs) geodynamic cycles. The impact of plate deformation phases prior to the collisional phase on the orogeny is still incompletely understood.

In this study, we present state-of-the-art 2D thermo-mechanical numerical models of a geodynamic cycle modelled in a single and continuous simulation including the following stages. First, a ca. 360 km wide basin that is floored by exhumed mantle and bounded by two conjugate magma-poor hyper-extended passive margins is generated during a 50 Myrs rifting period. An absolute extension velocity of 1 cm/yr is applied. Second, no far-field plate deformation (extension velocity of 0 cm/yr) is applied to the evolved passive margin system during a subsequent period of 60 Myrs. At this stage, we parameterise a serpentinization front on top of the exhumed mantle by replacing the dry peridotitic mantle by serpentinized mantle in one series of simulations. Third, the evolved system is used as a self-consistently generated initial configuration for the subsequent period of convergence lasting for 70 Myrs applying an absolute convergence velocity of 1.5 cm/yr. Values for the duration of deformation periods and for deformation velocities are chosen to allow for comparison between simulation results and geological and petrological data from the Central and Western Alps.

We quantify (1) the impact of a serpentinization front of the exhumed mantle on the subduction dynamics by increasing systematically the strength of the serpentinites, (2) the peak pressure and temperature conditions of subducted crustal material from the passive margins of the overriding and subducting plate by tracking pressure (P)-temperature (T)-time (t)-depth (z) paths of selected particles and (3) the driving forces of the system. Last, (4) the impact of metamorphic phase transitions is investigated by parameterising densification of crustal material. We compare the results of simulations in which density is computed with a simple equation of state to results of simulations in which density is a more realistic function of P and T using precomputed thermodynamic look-up tables.

We discuss geometric similarities between the simulation results and 2D geodynamic reconstructions from field data, quantify the P-T-t-z-history of selected particles and compare it to P-T-t data obtained from natural rocks. First results indicate that the strength of the serpentinites controls whether the deformation within the orogenic core is driven by buoyancy forces (subduction channel model) or by far-field tectonic forces (orogenic wedge model). There is a transition from subduction channel to orogenic wedge model from low to intermediate strength of the serpentinites.
P 1.6
Full 3-D pseudo-transient finite difference modelling of stress distribution around continental plateaus

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Collisional environments can form continental plateaus, such as the Tibetan plateau, which are characterized by an unusually large crustal thickness. The crustal thickness and topography variations between the plateau and the neighboring lowlands generate lateral variations of gravitational potential energy per unit area (GPE). Although plateau and lowland are in isostatic equilibrium, the lateral GPE variations must be balanced by horizontal differential stresses, which prevent the plateau from flowing-apart instantaneously. These differential stresses have been quantified with analytical solutions and numerical simulations, but mainly for two-dimensional (2-D) and rectangular geometries. Stress magnitudes and distributions around plateau corners for 3-D geometries and for realistic spherical geometries of the Earth are largely unknown. Indeed, quantifying these stresses and their spatial variation in 3-D is computationally challenging. Here, we present new 2-D and 3-D numerical algorithms, programmed in MATLAB (mathworks.com), to solve the Stokes equations under gravity. The algorithm is based on an Eulerian pseudo-transient finite difference method. The pseudo-transient method allows an explicit solution of the Stokes equations without the need of inverting a large stiffness matrix. When the pseudo-transient time derivatives approach zero, a steady-state solution for the velocity, strain rate and stress fields is obtained. The aim of developing these pseudo-transient algorithms is to eventually adapt them to GPU architectures, using the Julia language (julialang.org), in order to obtain highly-efficient high-resolution algorithms for 3-D numerical simulations. We present the current versions of the 2-D and 3-D algorithms for Cartesian, cylindrical and spherical geometries as well as numerical benchmarks and convergence tests.
P 1.7
The rheology and mechanical anisotropy of a foliated blueschist

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Blueschists are a major constituent rock type along the subduction zone interface and therefore critical to our understanding of subduction zone dynamics. Previous experimental work on natural blueschists focus on either seismic anisotropy or on the process of eclogization of a blueschist aggregate. We have begun an experimental investigation to constrain the rheology and mechanical anisotropy of a naturally foliated blueschist from the Condrey Mountain Window, CA. General shear experiments were performed in a Griggs apparatus using cores of the natural blueschist at 700°C, 1 GPa, and a shear strain rate of ~10-5 s-1. The starting material consists of ~55% glaucophane, ~40% epidote, <5% quartz and <5% mica where both glaucophane and epidote have strong crystallographic fabrics and shape-preferred orientations that define the foliation. Two types of experiments were performed: 1) with the foliation parallel to the shear plane and 2) with the foliation parallel to the sigma1 direction. Both experiments achieved a similar peak shear stress of ~250 MPa; however, the sample with the foliation parallel to the shear plane shows strain weakening while the sample with the foliation parallel to the sigma1 direction shows no strain weakening. We also observed several stress drops of ~20-30 MPa in the sample with the foliation parallel to the sigma1 direction prior to peak stress conditions. Additional experiments will be performed on these two deformation geometries at various stress and temperature conditions. A third type of deformation experiment will also be performed where the starting material has no foliation. A detailed microstructural analysis will accompany the mechanical results.

P 1.8
Experimental investigation of glaucophane rheology through shear and axial compression Griggs rig experiments on hot-pressed aggregates

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Constraining the rheological properties of glaucophane is critical to understanding subduction zone dynamics. Based on the rock record, glaucophane is a major constituent mineral associated with mafic oceanic crust at blueschist metamorphic facies. Previous experimental work on glaucophane focuses on the deformation of natural polyphase rocks with an emphasis on seismic anisotropy. Here we perform general shear and axial compression deformation experiments on synthetic glaucophane aggregates in a Griggs apparatus. The synthetic aggregates were produced through mineral separation of a natural blueschist from Syros, Greece. After mineral separation, the powders contain ~95% glaucophane with ~5% omphacite and epidote. We will present mechanical and microstructural data from constant displacement and strain-rate stepping experiments with the aim of developing a glaucophane flow law. Our results will also be compared to ongoing experiments focused on the viscous properties of experimentally deformed natural aggregates (see abstract in this conference by Tokle et al.).
Towards a model of the pre-Mesozoic basement beneath the Jura Mountains fold-and-thrust belt

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The Jura Mountains fold-and-thrust belt (JFTB) lies in the northern foreland of the European Alps, extending from eastern France to northern Switzerland. The JFTB formed as a result of Late Miocene to Pliocene northwest directed compression exerted by the orogenic wedge of the Alps and was sheared off its basement along a décollement in Triassic evaporites (Buxtorf, 1907; Laubscher, 1961). Prior to this, the pre-Mesozoic basement was intensely pre-structured, showing faults that had been active under changing stress fields during the Mesozoic and Cenozoic structural evolution of continental Europe. Main events were the opening of the Alpine Tethys in Early and Middle Jurassic, the formation of the Eocene to Oligocene European Continental Rift System (ECRIS, Dézes et al., 2004) and the formation of a flexural foreland basin during the subduction of the European lithosphere underneath the African plate (Laubscher, 1992). In order to understand the connection between thin-skinned JFTB formation and pre-existing basement structures, we created a digital surface model of the top of the pre-Mesozoic basement in the area of the detached Northern Alpine Foreland (NAF), and we paid particular attention to include faults with notable vertical offsets (in excess of 50 m). Although the lateral extent of the JFTB is controlled by the distribution of Triassic evaporites, our model demonstrates that individual structural domains as well as the position of the thrust front are linked to structures in the pre-Mesozoic basement. In some cases, structural orientations of the JFTB are conclusively connected to known discrete fault zones in the basement. Fault zones in the pre-Mesozoic basement follow structural trends that suggest the reactivation of inherited fault systems originating from the Variscan orogeny and post-Variscan collapse, such as proposed for segments of the ECRIS in Illies (1962) or Dézes et al. (2004). Our model of the pre-Mesozoic basement suggests that the fold and thrust geometry of the Jura Mountains was pre-determined and conditioned to a very high degree by structures in the pre-Mesozoic basement. This allows us to discuss varying structural elevations, the occurrence of oblique ramps or major strike-slip systems in the JFTB in a different light. We would like to encourage a holistic perspective on the JFTB and the detached NAF, which regards thin-skinned tectonics and basement tectonics neither as independent nor as strictly sequential.

REFERENCES

The anatomy of the basal shear zone of the High-Pressure Adula nappe and its repercussion on the Alpine regional geology

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Crustal shear zones commonly exhibit constrictional structures at all scales due to intense non-coaxial deformation. Within such deformational regime the lithological units are stretched and elongated along the shear direction, locally losing their lateral continuity. The missing continuity of marker horizons or diagnostic rocktypes challenges the large-scale geological mapping and sometimes causes misleading regional interpretations.

Here, we present detailed geological maps and profiles (scale 1:10'000) along the shear zone of the lower boundary of Adula unit, the largest High-Pressure nappe of the Central Alps. Overall, the lithological units along this shear zone show a sub-horizontal penetrative foliation (at amphibolite metamorphic facies) parallel to the lithological contacts that dip gently E to the SE. On the foliation plane the mineral and stretching lineation and the fold axis are oriented almost N-S independently on the orientation of the schistosity. However, within this general trend, the lithological boundaries and the foliations may rotate steeply to the E or to the W shaping the gneissic bodies (mostly orthogneisses) as prolate ellipsoids, elongated parallel to the mineral and stretching lineation. Locally, folds with axis parallel to the prolate ellipsoids depict, on the plane orthogonal to the lineation, concentric- or Ω-shapes typical of sheath folds. Large-scale Ω-folds have been mapped in the Pontirone and in the Misox valleys, in the latter case the upright Ω-fold forms the controversial Lostallo tectonic window that exposes the lower unit of the Simano.

We conclude that the most complete explanation for these complex structural patterns is the progressive constrictional shear regime, without invoking polyphase deformation, during the emplacement of the Adula Nappe in the Eocene-Oligocene.
P 1.11
Ground displacement analysis of the 1975 Kalapana earthquake (south flank of Kīlauea volcano) using air photo correlation.

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The Kīlauea volcano is composed of several structural components, with the Kīlauea caldera, the East and Southwest Rift zones, the Koa'e and the Hilina fault systems and a deep detachment. Most of these structural components are related to the volcano flank instability. The origin, the relation and the evolution of the active fault systems on the south flank (e.g. Koa'e and Hilina) is still poorly understood, including its role in magma storage in the area and the overall flank instability evolution. Here we focus on the magnitude 7.7 earthquake (29 November 1975) that triggered ground displacement of several meters all over the south flank of Kilauea volcano. Ground displacement occurred along a 25 km long sector of the Hilina and Holei fault systems with vertical and horizontal displacement along preexisting fault scarps. Our aim is to extract and to quantify the displacement that occurred during the event using air photo correlation and geodetic data to better understand the overall volcano flank dynamics.

To quantify the coseismic ground displacement, we use an optical imagery correlation technique. We analysed the 1975 earthquake using 12 and 15 photos for the pre-event (October 1974 and July 1975, respectively) and 6 and 12 photos for the post-event time period (December 1976 and March 1977, respectively). Both aerial photo datasets allow investigating the entire sector of Hilina and Holei fault system. Results show ground displacements of several meters on Kilauea's south flank (Hilina fault system and Holei Pali), in agreement with EDM measurements of 8 meters horizontal displacement measured at the coastline. These data will later be integrated with leveling data to provide better quantification and constraints on ground deformation during the event.

P 1.12
Spatial and temporal characteristics of deep seismicity beneath the Himalayas

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The Himalayan orogen, formed by the continental collision between the Indian and Eurasian plates, is one of the most tectonically active regions in the world. A large number of geophysical data and previous studies have shed light on the mountain-building processes and lithospheric structure of the orogen. The temporal and spatial characteristics of the deep seismicity, however, is somewhat limited. Thus, compiling an extended catalog for the Himalayan deep earthquakes is of great importance.

To create this catalog, we collected all the available continuous seismic data that operated during the last two decades in the Himalayas region (networks mostly operated between the following periods: 2001-2005 and 2013-2016). We started with the earthquake origin times of all the available deep earthquakes (i.e., hypocentral depths >50 km) from data centers and previous studies. We applied a systematic processing routine (e.g., picking P- and S-wave phases), and we obtained absolute earthquake locations using a 1D velocity model. We have calculated 729 preliminary earthquake locations based on high-quality picks. We intend to refine these preliminary absolute earthquake locations and calculate local magnitudes. Using this catalog, we plan to examine the temporal evolution and characteristics of the Himalayan deep seismicity. This information may help provide a better understanding of the local processes and mechanisms controlling seismogenesis at the root of the orogen.
The Northern Alpine foreland is divided into two domains: the Molasse Basin and the Jura FTB, both transported towards NNW. These domains are detached from the mechanical basement above a Triassic décollement. Thrusts and strike-slip faults affect the detached Mesozoic and Cenozoic sedimentary cover of the area. The Geneva Basin, located in western Switzerland, is part of the Plateau Molasse within the Molasse Basin and is limited to the NNW by the Jura FTB and to the SSE by the Subalpine Molasse. In the frame of the 2020 Geothermal project of the Canton Geneva, it is of major interest to constrain the subsurface geology of this area.

The aim of this project is to improve our knowledge on the geometry, the kinematics and the stress associated with the structures developed in the Geneva Basin and the adjacent Jura FTB.

Based on existing data and on new seismic interpretations, the first objective is to build a 3D geological model and balanced NW-SE cross-sections across the basin. In the Geneva Basin, the first results show that strike-slip faults are mainly oriented NW-SE and E-W and may be related to topographic differences of the top basement at the base of the Mesozoic series ("Vuache" or "Cruseilles" faults). Most of the anticlines and synclines show a NE-SW orientation, perpendicular to the general compressional direction. Along these anticlines, « shallow thrusts » in the Mesozoic cover appear to be rooted in intermediate detachment levels, possibly in the marls of the lower part of the Malm interval. A new detailed tectonic surface map makes it possible to better constrain the interpretation of structures even in the center of the Geneva Basin, and particularly in the area south of the E-W topographic lineament crossing the Mont-Sion pass. An important structure has also been observed close to the Humilly-02 well, and is interpreted as a NE-SW synsedimentary listric fault with possible salt flow. This structure has subsequently been reactivated and moderately inverted.

Numerical modelling will complement the structural and kinematic study, in order to better understand the structure development of the area and their related stress field. Based on existing and newly constructed cross-sections, a parametric analysis will be conducted to explore several hypothesis especially on the fault geometry of the area. Using a simplified geometry will subsequently allow us to constrain the mechanical context of the section. This will then help to generate hypothesis regarding structures that are poorly imaged, for instance the geometry of the footwall of the Salève Mount, or the nature of the faults in the Geneva Basin. A corresponding current stress field will be derived for each scenario.

Confronting results from the stress analysis and the kinematic/geometric model will allow us to address issues of strain partitioning as well as the sequence of fold and thrust development.
P 1.14
Seismotectonic evidence for active transtension along the Bodensee-Hegau Graben in the low-strain region of the northern Alpine Foreland

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The Hegau-Bodensee Graben (HGB), a major tectonic element in the northern foreland of the European Alps, is characterized by comparatively slow deformation rates (<1 mm/yr) and low seismicity. To understand the present-day deformation regime of this graben system, a seismotectonic study was performed, which builds on the seismological analysis of a series of recent earthquakes, recorded by an exceptionally dense, high-quality seismic monitoring network. The resulting high-precision absolute and relative hypocentre relocations, in combination with available focal-mechanisms, allow to identify geometry and kinematics of seismogenic structures in the upper crust, which can be related to the bounding faults of the NW-SE striking graben.

At its southwestern boundary, we associate micro-seismicity in the region of Schlattingen (northern Switzerland) with neotectonic activity along the Neuhausen Fault. Seismic velocities in the hypocentral area derived by recent tomographic studies, as well as structural models from seismic reflection surveys suggest that the seismically active part of the Neuhausen fault locates within the crystalline basement in a depth of about 5 to 6 km. Relative relocations and focal mechanisms image a NE-dipping normal fault, with indications for a listric geometry. On the opposite side of the graben, recent energetic earthquake swarms (magnitudes up to ML3.7) in the Hegau region near the town of Hilzingen and on the Bodman peninsula near Constance image graben-parallel faults. The earthquakes close to Hilzingen locate in depths of 5-6 km and are presumably located within the crystalline basement. The earthquake sequence near Constance locates shallower in about 3 km depth, indicating a source in the pre-Mesozoic basement. Associated focal mechanisms indicate normal to transtensional deformation in both cases.

Statistical analysis as well as stress inversion is performed for all available focal mechanism. Preliminary results indicate that today, an overall transtensional deformation regime prevails across the graben system. These results are in good agreement with the present-day stress field of the region, suggesting that the foreland of the Alpine collision zone is characterized by a present-day tectonic regime of strike-slip to normal faulting. Along preferentially oriented, pre-existing deformation zones, such as the NW-SE striking Hegau-Bodensee Graben oriented almost perpendicular to the regionally constrained minimum horizontal stress axis, this regime apparently allows for seismogenic dilatational faulting in an otherwise low strain region.