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Swiss Tectonics Studies Group of the Swiss Geological Society

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1.1

**New 3D microseismic tomography model interpretation and principal stress axes analysis in the Fribourg area (Swiss western Molasse Basin)**

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An increased level of local microseismicity was recorded over the past decade within the Fribourg region (Kastrup et al., 2007). Since 2010, two portable sparse mini-arrays were deployed to enhance seismic monitoring capabilities in that area. The waveforms recorded by these arrays, together with those recorded by local stations of the Swiss Seismological Service (SED), were analyzed using supersonograms (Sick et al., 2012) in order to detect very weak (ML ≥ 0.5) events. By significantly lowering the detection threshold, 314 events were detected in the Fribourg area from the detection of continuous record since 2010 and discontinuous record back to 2001, of which 112 events were detected routinely by the SED until 2013. After filtering, the arrival time data and raypaths of 200 high-quality events and 16 identified quarry blasts were selected for a microseismic tomography analysis.

The first stage of the microseismic tomography analysis consisted in building up an initial 3D P-wave velocity model, which was designed on the basis of: a) interpretations of controlled-source seismology data by NAGRA (National Cooperative for the Disposal of Radioactive Waste), b) time-depth chart of boreholes in Swiss Molasse Basin (Sommaruga et al., 2012), and c) complex 3D velocity model of Switzerland used by the SED for earthquake location. The tomography analysis was carried out with SIMULPS2000 (Thurber & Eberhart-Phillips, 1999). The output model has a minimal horizontal grid spacing of 8 km and vertical grid spacing of 700 m. That model was interpreted with prior knowledge of the area, such as cross-sections from Seismic Atlas of the Swiss Molasse Basin (Sommaruga et al., 2012). A vertical increase of velocity was observed to be linked to the density change of different lithological units as a function of depth. The model also displays lateral velocity increases (NW to SE) from the Molasse Basin through the Subalpine Molasse and Prealps.

The 3D microseismic tomography model was also used to evaluate principal stress axes in the Fribourg region. Take-off angles of events were estimated from the tomographic model and then combined with the first motion polarity of P-wave to estimate the orientation of principal stress axes and the focal mechanism of each event. Focal mechanisms solutions were calculated using FPFIT, which is a software used by the U.S. Geological Survey. Focal mechanisms were sorted and grouped on the basis of their uncertainties and their 3D spatial distribution. Solution quality was assigned according to the World Stress Map Project Guidelines for quality ranking (Barth et al., 2008). Our analysis shows that the principal stress axes derived from local earthquakes have the characteristics of the regional tectonics system: P-axis toward NW and T-axis toward SW with mostly strike-slip faults.

**REFERENCES**


1.2
Thin- vs thick-skinned tectonics, nappe formation and shear localization: numerical simulations and applications to the Helvetic Alps and Jura mountains

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Fold-and-thrust belts can exhibit two tectonic styles. Thin-skinned tectonics is characterized by stacks of allochthonous sedimentary nappes which have been displaced far away from their original basement. Thick-skinned tectonics involves the deformation of basement rocks to which are often associated (para)-autochthonous sedimentary nappes. It is still unclear what controls the development of one or the other tectonic style, whether it is tectonic inheritance, rheology or thermal conditions. In this study we used two dimensional (2D) thermo-mechanical numerical simulations to simulate the deformation of an idealized passive margin in compression. We investigated the control of stratigraphy, rheology, thermal conditions and initial geometry on the development of thick- or thin-skinned dominated tectonics. Results suggest that the viscosity ratio between the base of the upper crust and the sediments at the basement-cover interface controls to first order the dominant deformation style. Weaker basal upper crust allows the closure of pre-existing half graben basins. The sediments expelled from these basins then acquire the shape of a fold nappe. On the contrary a stronger basal upper crust inhibits basement deformation, which leads to the developments thrust-like horizontal weakly localized sheared zone, even in material with linear viscous rheology. This work has implication for the mechanics of emplacement of the Morcles fold nappe, Wildhorn and Glarüs thrust sheets and the Jura mountains.

Figure 1. Evolution of two simulations with non-linear (n=4) rheology from 0% to 50% shortening. Patterns indicate initial viscosity, colors code for the second invariant of the finite strain tensor (a-f) The lower basement layer has the same viscosity as the upper basement (crosses pattern). Deformation is dominantly thin-skinned, horizontal weakly localized shear zones developed; (g-l) The lower basement is 1000 times weaker than the upper basement. Deformation is dominantly thick-skinned. Sediments expelled during the closing of half-grabens form fold-nappe-like structures.
1.3

Geospeedometry in inverted metamorphic gradients of the Nestos thrust zone in central Rhodope (Northern Greece)

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Thrust tectonics and inverted metamorphic gradients are major consequences of large and likely fast movements in compressional environments. The purpose of this study is to investigate the tectonic setting and the timescale of inverted metamorphic zonations related to crustal-scale thrusting. The aim is to contribute understanding the link between mechanical and thermal evolution of major thrust zones and to clarify the nature and the origin of orogenic heat.

The Rhodope metamorphic complex (Northern Greece) is interpreted to be a deformed segment of the Alpine-Himalaya sutures and represents a collisional system with an association of both large-scale thrusting and pervasive exhumation tectonics. The Nestos Shear Zone overprints the suture boundary with a NEE-dipping pile of schists displaying inverted isograds. The inverted metamorphic zones start from chlorite-muscovite grade at the bottom and reach kyanite-sillimanite grades with migmatites in the upper structural levels.

In order to reconstruct the regional thermo-tectonic evolution of inverted metamorphic zonation, reliable geochronological data are essential.

U-Pb sensitive high resolution ion microprobe (SHRIMP) zircon geochronology on leucosomes from migmatitic orthogneisses were considered to estimate the age of peak metamorphic conditions, contemporaneous with anatexis. 40Ar/39Ar dating with step-heating technique on white mica from micaschists provided a temporal resolution with the potential to characterize shearing.

U-Pb ages of zircon rims extracted from migmatitic leucosomes specify regional partial melting during the Early Cretaceous (160-120 Ma). This is in disagreement with previous assertions, which argued that the formation of leucosomes in this region is Late Eocene (42-38 Ma) and implied multiple subductions and multiple metamorphic cycles during orogeny.

40Ar/39Ar dating across the Nestos Shear Zone yields Late Eocene-Early Oligocene (40-30 Ma) cooling (~400-350 °C) ages, which correspond to local thermo-deformation episodes linked to late and post-orogenic intrusions. Garnet geospeedometry considers the kinetic response of minerals and allowed estimating the absolute time-dependent thermal evolution by diffusive element profiles in garnet. Preliminary results of Fe-Mg – Ca – Mn garnet diffusion modelling indicate very short timescale (~1 Ma) for peak metamorphic conditions in the Rhodope collisional system.

1.4

A chronology of internal wedge deformation constrained by strontium isotopes of carbonate veins

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Here we present a new approach to assess the conditions and relative timing of deformation within accretionary wedges by means of radiogenic strontium isotopes of vein carbonates. Our study area is located within the Paleogene accretionary complex of the central European Alps comprising a <5 km thick sequence of Upper Cretaceous to Eocene shelf sediments and syn-orogenic turbidites. We sampled different generations of carbonate veins that were formed during accretion related reverse faulting, nappe stacking, sediment compaction, folding, normal faulting, and extensional hydrofracturing. We show that the 87Sr/86Sr of these veins record the evolution from an initially seawater derived fluid toward a diagenetic-metamorphic fluid. Our approach enables us to resolve the conditions and relative timing of these different deformation events on a resolution that cannot be assessed by cross-cutting relationships solely.
1.5 Internal geometry in the Sesia Zone (Aosta Valley, Italy)

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The Sesia Zone in the Western Alps is a HP terrain comprising fragments derived from the Adriatic continental margin. The classical subdivision of the Sesia Zone is based primarily on dominant lithotypes, as reflected in the names, from internal to external parts: Eclogitic Micaschist Complex (EMC), Seconda Zona Diorito-Kinzigitica (2DK), and Gneiss Minutti Complex (GMC). Any effort to delineate the complex tectonic structure and understand its assembly must combine structural mapping of the polydeformed terrain with a sufficiently detailed analysis of its polymetamorphic record (e.g. Gosso, 1977).

Such attempts have been made (Babist et al., 2006) and have again recognized three (slightly different) main units / nappes. However, recent petrochronological and structural work in what was considered one internal unit has revealed that it comprises at least two tectonic slices that experienced substantially different PTdt-evolutions (Regis et al., 2014). While the boundaries between these slices have proven difficult to localize, Regis’ study made it clear that further work is required to delineate contacts among such subunits and to quantify the PTdt-evolution for each of them. Understanding such a complex terrain demands an approach that is regional in scope, uses state-of-the-art techniques to analyze select samples, and integrates the results into a tectonic model.

Regional detailed petrographic and structural mapping (1:3k to 1:10k) was therefore undertaken with extensive sampling for petrochronological analysis. Based on this work, a first tectonic scheme is proposed here for the Sesia Zone between the Aosta Valley and Val d’Ayas, where all three classically recognized units are present in excellent outcrops. Some of this area already had been mapped by Pascquier et al (1981), Vuichard (1989) and Stünitz (1989), but no consensus exists on the location and geometry of units. In view of the structural complexity and variable metamorphic overprint, a set of sober criteria was developed and applied, aiming to delimit the first order tectonic units. The approach rests on three criteria, and these have proven useful for the purpose: (1) Discontinuously visible metasedimentary trails, primarily of carbonates, (2) mappable high-strain zones; and (3) visible differences in the metamorphic imprint. Each of these, taken alone, may pose problems. For instance, certain metasedimentary trails are clearly polydeformed (containing HT relics of Paleozoic age), but others seem to be monometamorphic, as they resemble Mesozoic lithotypes and show no HT relics; some shear zones show evidence of reaction activation and thus are difficult to correlate; retrograde effects occurring at cm- to km-scale vary with the early HP-imprint. Therefore, none of the key features used are by themselves sufficient, but in combination they allow us to propose a new map that delimits ten sizeable units: some are lens-shaped, whereas others are laterally more uniform, but all of them comprise various lithotypes.

We propose an Internal Complex with three eclogite sheets, each 0.5–3 km thick, from internal to external: Croix Courma sheet, Loses Blanches sheet, Prael sheet. Dominant lithotypes include micaschists associated with mafic rocks and minor orthogneiss. The main foliation is of HP, dipping moderately NW. Each of these sheets is bounded by (most likely monometamorphic) sediments, 10–50 m thick. HP-relics (of eclogite facies) are widespread, but a greenschist facies overprint locally is strong close to the tectonic contact to the neighboring sheet.

An Intermediate Complex lies external to the Prael sheet and comprises two thinner units called slices: the Simonetta-Pian slice is composed of siliceous dolomite marbles, meta-granites and -diorites with few mafic boudins. The main foliation dips SE and is of greenschist facies, but orthogneiss and garnet occur as relics. Towards the W (east of Mont Craban), this slice makes way to a strongly dismembered package that is considered to be a shear zone: Glaucophane-garnet phengite gneiss and minor orthogneiss bands are found repeatedly interlayered with impure dolomitic marbles. Gneiss fragments vary in thickness from centimeters to several meters, with phengite ± glaucophane-orthogneiss locally forming lenses within the marbles. The entire Intermediate Complex, some 500 meters wide on the ridge between Mont Craban and Priail, is reduced to a few meters towards SW. The main greenschist foliation dips moderate SE but a previous HP foliation, marked by glaucophane and phengite, is still recognizable; it lies parallel to the younger one.

In the External Complex, several discontinuous lenses of 2DK-lithotypes occur, and these are aligned with greenschist facies shear zones mapped within the GMC. By combining these features, three main sheets can be delimited (from internal to external: Craban sheet, Dondeuil sheet and Chasen sheet). The main foliation in all of these is of greenschist facies; it dips moderately SE. Fragments of 2DK gneiss collectively outline two tectonic slices wedged in between the above three sheets: Aquila-Lago slice and Nery-Torché slice.

Petrological work and in situ U-Th-Pb dating of accessory phases is underway to reconstruct the PTdt-history of several of these subunits of the Sesia Zone.
On craton destruction: Insight from 2D thermal-mechanical numerical modeling

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Although most cratons maintain stable, some exceptions are present, such as the North China craton, North Atlantic craton, and Wyoming craton, which have experienced dramatic lithospheric deformation/thinning. Mechanisms triggering cratonic thinning remains enigmatic [Lee et al., 2011]. Using a 2D thermo-mechanical coupled numerical model [Gerya and Yuen, 2007], we investigate two possible mechanisms: (1) stratification of cratonic lithospheric mantle [Liao et al., 2013; Liao and Gerya, 2014], and (2) rheological weakening due to hydration.

Lithospheric mantle stratification is a common feature in cratonic areas which has been demonstrated by geophysical and geochemical studies [Thybo and Perchuc, 1997; Griffin et al., 2004; Romanowicz, 2009; Rychert and Shearer, 2009; Yuan and Romanowicz, 2010]. The influence of lithospheric mantle stratification during craton evolution remains poorly understood. A rheologically weak layer representing hydrated and/or metasomatized composition is implemented in the lithospheric mantle. Our results show that the weak mantle layer changes the dynamics of lithospheric extension by enhancing the deformation of the overlying mantle and crust and inhibiting deformation of the underlying mantle [Liao et al., 2013; Liao and Gerya, 2014]. Modeling results are compared with North China and North Atlantic cratons. Our work indicates that although the presence of a weak layer may not be sufficient to initiate craton deformation, it enhances deformation by lowering the required extensional plate boundary force.

Rheological weakening due to hydration is a possible mechanism triggering/enhancing craton deformation, especially for cratons juxtaposing with subduction zones, since water can release from subducting slabs. We investigate the influence of wet mantle flow laws [Hirth and Kohlstedt, 2003], in which a water parameter (i.e. constant water content) is involved. Our results show that wet dislocation alone does not accelerate craton deformation significantly. However, if wet diffusion creep is incorporated, combined effect of wet dislocation and wet diffusion creeps enhance lithosphere deformation dramatically. Lithospheric material drips off rapidly from the lithosphere base to asthenosphere, and thins lithosphere by ~ 40 km.

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The tectonometamorphic evolution of the Sesia – Dent Blanche nappes (internal Western Alps)

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This study reviews and synthesizes the present knowledge on the Sesia – Dent Blanche nappes, the highest tectonic elements in the Western Alps, which comprise pieces of pre-Alpine basement and Mesozoic cover. All of the available data are integrated in a crustal-scale kinematic model with the aim to reconstruct the Alpine tectono-metamorphic evolution of the Sesia – Dent Blanche nappes. Although major uncertainties remain in the pre-Alpine geometry, the basement and cover sequences of the Sesia - Dent Blanche nappes are seen as part of a thinned continental crust derived from the Adriatic margin.

The earliest stages of the Alpine evolution are interpreted as recording late Cretaceous subduction of the Adria-derived Sesia - Dent Blanche nappes below the South-Alpine domain. During this subduction, several sheets of crustal material were stacked and separated by shear zones that rework remnants of their Mesozoic cover. The recently described Roisan-Cignana Shear Zone of the Dent Blanche Tectonic System (Manzotti et al. 2014) represents such a shear zone, indicating that the Sesia – Dent Blanche nappes represent a stack of several individual nappes. During the subsequent subduction of the Piemonte-Liguria Ocean large-scale folding of the nappe stack (including the Roisan-Cignana Shear Zone) took place under greenschist facies conditions, which indicates partial exhumation of the Dent Blanche Tectonic System. Finally, the entrance of the Briançonnais micro-continent within the subduction zone led to a drastic change in the deformation pattern of the Alpine belt, with rapid exhumation of the eclogite-facies ophiolite-bearing units and thrust propagation towards the foreland. Slab breakoff probably was responsible for allowing partial melting in the mantle and Oligocene intrusions into the most internal parts of the Sesia - Dent Blanche nappes. Finally, indentation of the Adriatic plate into the orogenic wedge resulted in the formation of the Vanzone back-fold, terminating the pervasive ductile deformation within the Sesia - Dent Blanche nappes during the earliest Miocene.

REFERENCES
New age constraints for the geodynamic evolution of the Sistan Suture Zone, eastern Iran

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The N–S trending Sistan Suture Zone (SSZ) in eastern Iran is attributed to eastward subduction beneath the Afghan continental block of an inlet of the Mesozoic Tethys Ocean. We present U-Pb zircon crystallization ages combined with petrography, major and trace element analyses, Hf isotopes, Rb-Sr and Sm-Nd isotopes of intermediate to granitic intrusions stretched along the southern segment of the SSZ. We obtained two clearly separated clusters of concordant ages, which are taken as the crystallization age of the host plutonic rocks. The first cluster, between ca 42.5 and ca 44.5 Ma from euhedral zircons of the main granodiorite to diorite and related dykes. The second age cluster span from ca 28.3 to ca 31 Ma. These ages were obtained for granites and dykes, the latter being consistently slightly younger than the country rock. The high SiO₂ content (62-75 wt %) of Eocene magmatic rocks points to melts with a high crustal contribution in consistency with their relatively high-K (3-4.4 wt %) calc-alkaline nature. The high SiO₂ and K contents in the Oligocene calc-alkaline rocks series shows adakite-like fractionation. Oligocene adakite-like rocks have relatively low to medium ⁸⁷Sr/⁸⁶Sr and ⁴⁴Nd/⁴⁰Nd ratios, which are similar to typical lower thick crust-derived adakites. The mix positive and negative ε⁴⁴Hf(T) values of all zircons from the 42.5-44.5 Ma shows mix nature of magma (the contamination of subduction related magma with partial melting of crust). The positive ε⁴⁴Hf(T) values of all zircons from the 28-31 Ma adakite-like rocks indicate that the magma was not produced from pure depleted mantle. Instead, they are consistent with a host magma source within a largely juvenile and subduction-related mafic lower crust. Eocene granitoids represent anatectic melts emplaced at higher crustal levels; in addition slab melts modified the mantle wedge and subsequent, contaminated mantle magmas fed intrusions such as the Zahedan diorite.

Figure 1. Plot of ¹⁴⁴Nd/¹⁴⁰Nd ratios versus ⁸⁷Sr/⁸⁶Sr ratios for comparison of Sr-Nd isotope compositions between Zahedan adakites and Zahedan and Shah Kuh magmatic rocks. DM: depleted mantle, EMI: enriched mantle type I has lower ⁸⁷Sr/⁸⁶Sr; EMII: enriched mantle type II has higher ⁸⁷Sr/⁸⁶Sr (>0.720).

Figure 2. Plot of epsilon-Hf(T) versus ²⁰⁶Pb/²³⁸U age (Ma) for Zahedan and Shah Kuh granitoids and dykes. Corrections in function of age are based on chondritic values (CHUR), which become the reference value.
1.9

Recurrence behavior of destructive earthquakes in Western Anatolia, Turkey: Insights from cosmogenic $^{36}$Cl dating method

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Instrumental records of destructive earthquakes in the Eastern Mediterranean and Middle East are only available for the last century and the historical ones date back only to 464 B.C. These are essential in order to assess how often significant earthquakes occur in a seismic-prone area and to forecast destructive events. However, since the major faults generally have return period of several hundreds of years, the time span of present seismic records is not long enough to precisely evaluate recurrence interval.

In this study, we focused on the normal faults within the graben systems of Western Anatolia in order to evaluate the earthquake recurrence time and reconstruct the paleoseismic history by employing fault scarp dating with cosmogenic $^{36}$Cl. Deformation pattern in the Western Anatolia region is governed by E-W trending major grabens of Gediz, Küçük Menderes, Büyük Menderes and Gökava, as a result of roughly N-S extensional regime since early Miocene. There, large scale normal faults are built in limestone with evidence of ruptures during the Pleistocene-Holocene, which generally separate high-topographic pre-Neogene rock units from shallow Quaternary basins.

Our results from Priene-Sazlı Fault segment in the westernmost part of Büyük Menderes graben indicate destructive earthquakes in Holocene, in concordance with existing earthquake records. This yields a regular recurrence interval of approximately 2000 years. Further north, the combination of historical records and paleoseismological data with fault-scarp dating of Manisa and Mugirtepe faults in Gediz graben shows an irregular recurrence time, which is decreasing through the time.

To improve our understanding of seismic behaviour of Western Anatolia since the Late Pleistocene, Kalafat and Yavansu faults within Büyük Menderes graben in SE of Kuşadası residential area, Ören fault scarp within Gökava graben close to Kemerköy thermal power plant as well as Rahmiye fault in Akhisar urban area were sampled and their analysis is in progress.
1.10

Numerical bifurcation study of the initiation of folding and necking in elasto-visco-plastic rocks

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Folding and boudinage of a competent layer embedded in a mechanically weaker matrix are commonly thought to exclusively develop due to interactions arising from geometry. However, there exists an additional localization phenomenon, i.e. strain localization out of steady state in a homogeneous material for a critical material parameter (set) or deformation rate. This theory is closely associated with strain localization due to ductile shear heating of viscous materials, as is the case for creeping calcite at shallow to mid-crustal levels.

We present a numerical setup which accounts for grain size variations, using the paleowattmeter relationship of Austin and Evans (2007). This scaling theory has recently been numerically implemented into a thermo-mechanical framework (Herwegh et al., 2014). In a first step, we identify the parameter set for bifurcation, which is the critical amount of dissipation over the diffusive capacity of the system, defined by the Gruntfest number (Gruntfest, 1963). This number incorporates flow stress, the Arrhenius number ($Q/RT$) and the layer dimensions. We verify the robustness of the solution through an analysis of the system’s sensitivity to material instabilities (Rudnicki and Rice, 1975). This second step aims at identifying the eigenfrequencies and natural mode shapes of the geometric structure and material parameters. In a third step, the eigenmodes are perturbed and superposed to the initial conditions. We then subject the composite structure to natural deformation conditions. Grain sizes within the layer relatively quickly equilibrate to a homogeneous state, which is in response to energy optimization following the paleowattmeter relationship. Upon continued loading, localization in terms of a necking or folding instabilities interestingly arise out of this steady state.

We obtain the criteria for the onset of localization from theory and numerical simulation, i.e. the critical Gruntfest number. Boudinage and folding instabilities occur when the mechanical work, which is translated into heat, overcomes the diffusive capacity of the system. Both instabilities develop for the exact same Arrhenius and Gruntfest numbers. We conclude that folding and boudinage instabilities can be placed at the same material behavior due to fundamental energy bifurcations triggered by dissipative work out of homogeneous state.

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Recent movements in the Alps: geodetic and GPS derived data

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The precise leveling data of swisstopo (e.g. Schlatter et al. 2005) show that the Alps are rising at a faster rate as compared to the Northalpine foreland. Relative to the fix point Aarburg the Central Alps are rising at around 1 mm/yr with two maxima in Graubünden and the Valais where rates of up to 1.5 mm/yr are reported. Whereas these uplift rates compare to the ones reported from the Austrian Alps, much higher rates have been published in the French Alps and the Southern Alps of Italy (Arca & Beretta, 1985). In a cross-section from Black Forest – Lucerne – Po Basin the rates as measured by the Swiss network drops across the Insubric Fault; at the junction with the Italian data a major discontinuity arises with rates being at least 1 mm/yr higher in the Southern Alps.

Considering the satellite derived uplift rates of the AGNES permanent network, the difference of uplift rates between the Northalpine Foreland to the Alps is also evident and more than 1 mm/yr. Interestingly the absolute rates of the GNNS data within the Alps are about 1.2 mm/yr higher as compared to the leveling data. Since the area of northern Switzerland (including Aarburg) is rising by about 1.2 mm/yr relative to the stable part of the European plate, the absolute uplift rate in the Alps must be even higher and might attain values of 3 mm/yr. The vertical uplift rates are in stark contrast to the horizontal velocities determined from the satellite derived data. The latter suggest a southward component of the Northalpine foreland of 0.2 mm/yr and a northward component of 0.35 mm/yr of the stations within the Alps if the above mentioned cross-section is considered. The resulting convergence rate of 0.5 mm/yr is much lower that the vertical uplift rate, indicating that the latter are likely to contain a component of large-scale buoyant rise. In map view the horizontal motions point to an extension parallel to the Alpine orogeny.

The uplift rates as determined from precise leveling show a high gradient across the Subalpine Molasse in the cross-section considered here. This corresponds to the latest thrust faulting within the Alpine orogen, the age of which is as young as 8 Ma. Interestingly, the apatite cooling ages are younger than 8 Ma in the areas of the two uplift maxima of Graubünden and Valais. It thus seems that the present day motions might reflect a continuation of the Neogene deformation.

The Subalpine Molasse also marks a transition from the foreland, where hypocenters of earth quakes are concentrated within the lower crust (Singer et al., 2014), and the Alpine orogen where hypocenters are restricted to the uppermost 10-15 km (Deichmann et al. 2000). Focal mechanisms sustain a component of NNW-SSE to NW-SE directed compression in the Alpine foreland in the Alps of central Switzerland, as opposed to an NE-SW extension within the Alps of Graubünden and N-S extension in the Valais.

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1.12

**Tectonics of the Monte Rosa nappe: Tertiary phases of subduction and thrusting in the Pennine Alps**

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The Monte Rosa basement fold nappe, surrounded by other continental units of the Briançonnais s.l. domain and ophiolites of the Piemont Ocean, represents a major structure of the Pennine Alps situated at the border of the Canton Valais (Switzerland) and Italy. The Central Alps were formed during the collision and SE-directed underthrusting of the European below the Adriatic plate by successive underthrusting, detachment and accretion of the Austroalpine Sesia continental crust, the Piemont oceanic crust and the continental Briançonnais-Europe plate border. The 90-60 Ma Sesia high-pressure metamorphism, followed by the 50-38 Ma Zermatt-Saas Fee and Monte Rosa high-pressure metamorphism and since 40 Ma by the Barrovian regional metamorphism reveal a long-lasting Alpine evolution during convergence of both plates. The superposition of the ultra-high pressure Zermatt-Saas Fee ophiolites by the continental Cimes Blanche unit of the Briançonnais domain and the medium pressure ophiolitic Tsaté nappe is explained by delamination and tectonic flake detachment of the Cimes Blanches from the Briançonnais crust and its south directed thrust over the Zermatt-Saas Fee ophiolites. The main ductile deformational structures, related to the NW-directed nappe emplacement, were generated after 40 Ma under greenschist to amphibolite facies Barrovian orogenic metamorphism. Early extrusional structures have been transposed by the younger thrust structures. The NW-directed thrust of the Alps was accompanied since about 35 Ma by ductile dextral shear and back folding in the zone of dextral transpression between the converging European and Adriatic plates.

REFERENCES


**1.13**

**4D Modeling of Transfer Zones in Continental Rifts**

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**INTRODUCTION**

Inherited structures in the Earth’s crust represent weak zones along which deformation will focus during subsequent extension. To develop a full-scale rift system, such initial faults will connect through transfer zones. Previous studies (e.g. Acocella et al., 1999) have focused on the modeling of these transfer zones and their geometries, but our study improves upon them by: 1) Modeling the entire continental crust; 2) Applying a more distributed type of deformation.

**MODEL SET-UP & METHODS OF ANALYSIS**

The experimental machine consists of two rigid sidewalls with a base of alternating plexiglass and foam bars in between (Fig. 1). By moving the sidewalls apart, the foam expands and fills the extra space. This allows a uniform deformation at the base of the overlying material. In addition, one of the base plates can move laterally, allowing strike-slip and transtensional set-ups.

Sand and silicone are used to represent the Earth’s crust. Lines of silicone on top of the basal silicone form pre-existing weak zones that localize deformation. Several models are analyzed with X-ray tomography (CT scanning, Fig. 1B and Fig. 3) to reveal the 3D evolution of internal structures with time (hence 4D).

**RESULTS**

Localizing deformation along weak zones works well, all models developed distinct rift structures (selection in Fig. 2). However, several models have no linkage between both rift zones. In this model set-up and contrary to previous studies, successful linkage is due to rift zone proximity instead of a connecting pre-existing weak zone. The strike-slip in the transtensional models created oblique features, perpendicular to the overall extensional direction, and a lateral displacement along the main rift. It is also clear that CT techniques offer promising potential for thorough model analysis (Fig. 3).
Figure 2. L: Model set-up (without sand cover) with weak zone geometry (white dotted lines) and deformation vectors (red arrows). R: resulting structures.

Figure 3. CT Imaging: A) 3D views of model Tz7, showing surface deformation with time; B) Sections of model Tz7 (location shown with dotted lines in A).

FUTURE MODELING
Future work within this project will focus on transtensional settings: testing different plate geometries and modeling of natural examples. Also collaboration with colleagues from the numerical domain will be arranged, to fully combine and exploit the possibilities of both sides of the modeling spectrum.

REFERENCES
P 1.1

Detrital zircon grains in blueschist-facies meta-conglomerates: implications for the early Permian geomorphology of the future northern margin of the Liguria-Piemonte ocean

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In the Western Alps, the Money Complex of the Gran Paradiso Massif, metamorphosed under blueschist facies during the Alpine cycle, is considered to be Permo-Carboniferous in age, but no palaeontological or radiometric data constrain this interpretation.

A revision of the lithostratigraphy of the Money Unit allows recognizing a polygenic (graphite-rich) and a monogenic (graphite-poor) meta-sedimentary formation. Detrital zircon U-Pb geochronology in both meta-sedimentary formations shows that (i) the main population is Cambrian and Ordovician in age, (ii) the youngest grains are Silurian and Early Devonian and (iii) Carboniferous zircon grains are lacking.

A careful study of the age distributions in the Alps suggests that potential source for the detrital material in the Money Complex is the Briançonnais basement. Late Carboniferous magmatism is widespread in the Helvetic Zone of the Alps. Permian magmatism is dominant in the Briançonnais, the Austroalpine and the Southalpine unit. The lack of Carboniferous zircons in the Money Complex suggests that the detritus was not shed from the Helvetic zone, which was separated from the Money basin by the Zone Houillère basin, where the main drainage pattern was developed from south to north and where the depocenters migrated northwards from the Namurian to the Stephanian.

We suggest that the Money Complex may had been located to the east of the main river drainage inside the Zone Houillère basin or alternatively may represent a small basin, located on the east of the Zone Houillère.

P 1.2

A new 1:100’000 scaled geological map of the Aar massif

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Over the past century, a vast number of spatially restricted but very detailed maps of the Aar massif were mapped, some of them already published in the Geological Atlas of Switzerland. By using the vector data of these maps, complemented with compilations that were created in the frame of the GeoCover project at swisstopo, we correlated lithologies, outcrop geometries and tectono-geodynamic units and harmonized them in the entire Aar massif. Harmonisation was done according to the principles of HARMOS in Switzerland (for details see HARMOS project at swisstopo) In combination with already existing compilations (Heim 1922, Labhart 1977, Oberhansli et al. 1988, Abrecht 1994, Steck et al. 1999), these maps served as a base to construct the new map. We present the result in form of a new geological map of the complete Aar massif ranging from the Lötschental in the W to the Tödi area in the E.

We summarized the lithologies in following groups:
(1) Mesozoic-Cenozoic cover, (2) Carboniferous-(Perminian) sediments and volcanics (Maderaner Group), (3) Middle Paleozoic metasediments (Cavardiras Group), (4) Asselian plutonic rocks (Central Aar group), (5) Pennsylvanian plutonic rocks (Brunni group), (6) Visean plutonic rocks (Tödi group) and (7) polycyclic basement units (»Altkristallins). The latter are subdivided into seven major groups: (7a) Innertkirchen-Lauterbrunnen zone, (7b) Erstfeldergneiss zone, (7c) Guttannen zone, (7d) Ofenhorn-Stämpfli zone, (7e) Grimsel zone, (7f) Lötschental zone and (7g) Ausserberg-Avat zone. Originially, these groups were defined for local rock assemblages. Based on the new compilation, we can extend the continuation of
these groups over the complete massif. This spatial continuity of old polycrystalline gneisses, Variscan to post-Variscan plutonites and volcanoclastic rocks, together with Mesozoic sediments, characterizes the large-scale structure of the Aar massif. Particularly deformation stages in the Maderaner group and Mesozoic sediments permit to differentiate the several tectonic movements and to understand the kinematics and geodynamics of the Aar massif. The overlapping strike of the different structures is only possible by the reactivation of pre-existing structures at different times. The map will serve as a base for further reconstructions of tectonic evolution during Mesozoic and Alpine times.

REFERENCES
P 1.3

Do surface processes and/or the presence of an initial surface topography affect(s) the fold linkage? And if yes, how?

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Landscape geomorphology provides an indirect observation of the tectonic activity. Surface processes and tectonics interact one with another to create a wide variety of landscape. Geomorphic features such as wind gaps can record the amplification and lateral propagation of embryonic fold segments. Depending of their relative initial spacing, those growing fold segments can link and form long train folds. This mechanism has been suggested for the Zagros Folded Belt, where the axial lengths of folds can reach more than 100 km.

Previous studies have focused on fold linkage or on the response of the drainage network to tectonic forcing. Using seeds in their setup to prescribe the fold orientation, Grasemann and Schmalholz (2012) numerically investigated the distance between two isolated laterally propagating folds to explain the different modes of linkage. However, the effects of surface processes on the fold development have not been considered.

Our recent multilayer folding experiments, in which an initial random perturbation was prescribed, have shown that under efficient drainage network conditions, or when a non-zero initial topography was applied to the model, the type of fold linkage could be modified. In this study we systematically investigate the effects of surface processes on the mode of linkage and how the distance between two isolated growing perturbations, required for linkage, is affected.

In order to address this question, we use the 3D thermo-mechanical code LaMEM, which has been coupled to a finite-element based landscape evolution model (both erosion and sedimentation). The landscape evolution model uses a non-linear diffusion formulation (Simpson and Schlunegger, 2003) taking into account both hillslopes and channel processes.

REFERENCES

P 1.4

Thermo-mechanical shear localisation: length scale and thermal imprint

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We present two-dimensional models of shear localization in geomaterials using laboratory derived flow laws. Under geologically relevant loading conditions, shear localisation is triggered by shear heating. The scale of such shear zones is physically controlled and hence does not depend on the numerical resolution. The width of such shear zones is the order of 1000 m, in agreement with some natural observations. A simple scaling law can be used to predict shear zone thicknesses and good agreement was obtained against systematic numerical models. We show the influence of non-linear and linear rheologies and investigate the impact of elasticity on the transient stages of shear localisation.

In a conservative system, shear localization takes place coevally with a temperature increase. We show that the thermal imprint is diffused across the shear zone whereas the strain remains localized inside the shear zone. Our results suggest that sharp temperature increases are not expected across shear zones, which is often observed in natural shear zones. This effect is amplified by taking into account a period of thermal relaxation after the deformation.
Kinematic analyses on multiply reactivated fault systems in the Black Forest – Hegau – Lake Constance region

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The Black Forest – Hegau – Lake Constance region lies in a geodynamically particular position at the boundary zone of the Jura fold-and-thrust belt, the northern Alpine flexural Molasse basin and the uplifted Black Forest basement massif. The shallowly east-dipping flank of the Black Forest massif and its overlying sediments, comprise rocks ranging from pre-Mesozoic basement, Mesozoic cover units, Tertiary Molasse deposits to Quaternary cover, thus allowing insight into the sedimentary and tectonic evolution across a wide range of lithological levels. This zone can therefore serve as a natural laboratory for understanding the nature of the subsurface of the Swiss and German Molasse basin, which is a zone of high potential geo-economical interest. The tectonic framework of the study area is largely influenced by the combined effect of two major Cenozoic tectonic events, namely the uplift of the Black Forest Massif and the formation of the Molasse basin in the northern Alpine flexural foreland. In the southern Black Forest and its sedimentary cover, one can observe a dense network of differently oriented fault sets, with the dominating directions being NNE-SSW (Rhenic), WSW-ENE (Variscan) and WNW-ESE to NW-SE (Hercynian) (e.g. Geyer et al. 2011). Many of these faults are likely to have been initiated and to have a precursor from at least Late Variscan times and are thought to have been reactivated during the Cenozoic deformation events. Such pre-existing structures can have a strong influence on the local tectonic response to a regional stress field. Most deformation is localized along larger faults and fault zones, the Freiburg-Bonndorf-Bodensee fault zone (FBBFZ, e.g. Carlé 1955) being the most important one. This system of faults runs from the Upper Rhine Graben across the Black Forest massif into the region of Lake Constance, thereby connecting the volcanic fields of the Kaiserstuhl and the Hegau. Deformation is dominated by normal faulting, forming a series of graben structures. However, on a smaller scale, strike-slip movements very often reactivate former normal faults and transcurrent deformation appears to become more important with time. This study uses structural field data as well as map-view analysis of fault distribution in order to evaluate the timing and the differing kinematics of the region. Furthermore, the behaviour and effect of inherited structures, their surface expression and their potential for neotectonic activity is being investigated. Kinematic analysis of outcrop-scale features along the FBBFZ show a strong dependency of the fracture characteristics on the fault system and it is suggested that deformation in the area is strongly influenced by pre-existing structures and local stress perturbations in the vicinity of larger fault zones, which have to be considered carefully in the light of the larger geodynamic model.

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Neotectonic Activity at the Front of the Alps: Earthquake-induced Geomorphology in the Aare Valley & Lake Thun

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Strong earthquakes (i.e. intensities >VI-VII) are considered as main triggers of subaquatic slope failures apart from collapsing shorelines and deltas due to their heavy sediment overload. Such earthquake-triggered mass movements occur frequently in Switzerland. Their triggers reflect recent tectonic activity in the Alpine region, and they have precisely been recorded by the Swiss Seismological Service (SED). The larger of these events (i.e. magnitudes >6) are expected to produce surface ruptures due to the size and displacement of the slipping surface. However, such ruptures can scarcely be found in the field as obvious imprinted geomorphologic features, such as offset moraine crests and fluvial terrace risers, deflected river courses and fault scarps, and are rare to absent. Likewise, only a few studies successfully showed the existence of an active fault cutting through Alpine nappe stacks (e.g. Sue et al. (2007), Ustaszewski et al. (2007)). Since erosional surface processes complicate the recognition of earthquake-caused topographic offsets, or often make it entirely impossible to trace them, the expected high preservation potential of a lake is the ideal environment to find such geomorphologic features.

This study uses a multi-disciplinary two step-approach to characterize potentially active faults in the Aare-valley between Interlaken and Bern. The perimeter crosses the North Alpine nappe front and hence lines up with the Lake Lucerne and Lake Zurich areas, which proved to show significant paleo-seismological activity along the Alpine arch and its foreland (Strasser et al., 2006). In addition to the earthquake catalogue of Switzerland ECOS-09 (Fäh et al., 2011), small-scale deformation structures (seismites), turbidite deposits and liquefaction structures ultimately prove the recent tectonic activity, and have all been observed in Lake Thun (Wirth et al., 2007).

In a first step, we will focus our investigation on Lake Thun starting with a review of high-resolution seismic data (3.5 kHz) of Lake Thun showing potential faults at the lake bottom (Wirth et al., 2011). This data will be complemented by a multibeam bathymetric survey, scheduled for September this year.

At a second stage, we will extend our investigation to terrestrial areas investigating LiDAR data and orthophotographs (courtesy of swisstopo), correlating lake findings with those on land. Promising identification of such features will be compared to the distribution of epicentres provided by ECOS-09 (Fäh et al., 2011).

The visual evaluation of the 3.5 kHz high-resolution seismic data revealed several structures, which deserve further analysis (see figure 1b). Earthquakes of moment magnitudes Mw 1.5 – 3.9 within and closely around Lake Thun were recorded, which though are too weak to trigger slope failures and hence were not imprinted in the sediment strata. However, the observed offset in figure 1b) might represent a potentially active area.

REFERENCES


Fig. 1: a) Overview of seismic campaign (blue lines) on Lake Thun with superimposed paleo-seismic events. b) Seismic section revealing a potential fault with offset indicated by black arrows (shown section marked with square).

P 1.7

Tectonics and Strain partitioning in the Mont Pèlerin Subalpine Molasse

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The Mont Pèlerin is situated between Vevey and Palézieux, in a vast NE to SW trending synclinal structure in the Subalpine molasse domain. The Mont Pèlerin is renowned for its important conglomeratic series produced by the erosion of the Prealpine Nappe de la Simme, during Chattian times (USM).

Overall the Mont Pèlerin area is structured by a serie of regional folds, as well as local small-scale folds, both determined from bedding dip data. It can be subdivided in three zones, depending of the orientation of the folds. In the southern part of Mont Pèlerin area, this folds orientation is E-W, whereas to the north the orientation shows the more typical alpine NE-SW trend. The western zone shows a more or less monoclonal east-dipping geometry. A gently SE dipping thrust surface cuts the whole upper part of the Mont Pèlerin and forms the flat portion of a regional ramp-flat thrust plane with a general transport top to the NNW. In addition, a series of important NW-SE to NNW-SSE trending strike-slip faults cut the whole structure. We view these faults as a possible extension of the conjugate fault system associated with the supra-regional Pontarlier fault to the NW in the Jura Mountains.

Deformations observed in the fields include: solution pits on pebbles, fractured pebbles, fractures, and veins. The study of the numerous solution pits on pebbles indicates two superposed deformations. A major pole density points to a subvertical compression that we tentatively attribute to the effect of loading due to burial in excess of four kilometers. A second maxima is oriented SSE with a gentle dip to the south. We attribute this latter to a regional compression associated with the general folding and thrusting.
Early Earth tectonics: A high-resolution 3D numerical modelling approach

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Early Earth had a higher amount of remaining radiogenic elements as well as a higher amount of leftover primordial heat (Jaupart et al., 2007). Both contributed to the increased temperature in the Earth’s interior and it is mainly this increased mantle potential temperature ΔTp that controls the dynamics of the crust and upper mantle and the style of Early Earth tectonics.

We conduct 3D petrological-thermomechanical numerical modelling experiments of the crust and upper mantle under Early Earth conditions and a plume tectonics model setup. For varying crustal structures and an increased mantle potential temperature ΔTp, a thermal anomaly in the bottom temperature boundary introduces a plume. The model is able to self-sufficiently form depleted mantle lithosphere after repeated melt removal. New crust can be produced in the form of volcanics or plutonics. To simulate differentiation the newly formed crust can have a range in composition from basaltic over dacitic to granitic depending on its source rock.

Compared to lower ΔTp where formation of a forearc can be observed, for ΔTp=200 K models show large amounts of subcrustal decompression melting and consequently large amounts of volcanics in the form of flood basalts. Mantle and crust are convecting separately. Dome-shaped plutons of mafic or felsic composition can be observed in the crust. Between these domes, circular or elongated belts of upper crust, volcanics and sediments of intermediate to felsic composition are formed and transported back into the mantle in a subduction like process. These structures look similar to, for example, the Kaapvaal craton in South Africa where the elongated shape of the Barberton Greenstone Belt is surrounded by multiple plutons (e.g. Van Kranendonk, 2011).

REFERENCES
Towards coupled giant impact and long term interior evolution models

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The crustal dichotomy (McCauley et al., 1972) is the dominant geological feature on planet Mars. The exogenic approach to the origin of the crustal dichotomy (Wilhelms and Squyres, 1984; Frey and Schultz, 1988; Andrews-Hanna et al., 2008; Marinova et al., 2008; Nimmo et al., 2008) assumes that the northern lowlands correspond to a giant impact basin formed after primordial crust formation. However these simulations only consider the impact phase without studying the long-term repercussions of such a collision.

The endogenic approach (e.g. Weinstein, 1995), suggesting a degree-1 mantle upwelling underneath the southern highlands (Zhong and Zuber, 2001; Roberts and Zhong, 2006; Zhong, 2009; Keller and Tackley, 2009), relies on a high Rayleigh number and a particular viscosity profile to form a low degree convective pattern within the geological constraints for the dichotomy formation. Such vigorous convection, however, results in continuous magmatic resurfacing, destroying the initially dichotomous crustal structure in the long-term.

A further option is a hybrid exogenic–endogenic approach (Reese and Solomatov, 2006, 2010; Reese et al., 2010; Golabek et al., 2011), which proposes an impact-induced magma ocean and subsequent superplume in the southern hemisphere. However these models rely on simple scaling laws to impose the thermal effects of the collision.

Here we present the first results of impact simulations performed with a SPH code (Benz and Asphaug 1995, Jutzi et al., 2013) serially coupled with geodynamical computations performed using the code I3VIS (Gerya and Yuen, 2007) to improve the latter approach and test it against observations. We are exploring collisions varying the impactor velocities, impact angles and target body properties, and are gauging the sensitivity to the handoff from SPH to I3VIS.

As expected, our first results indicate the formation of a transient hemispherical magma ocean in the impacted hemisphere, and the merging of the cores. We also find that impact angle and velocity have a strong effect on the post-impact temperature field (e.g. Marinova et al., 2008) and on the timescale and nature of core merger.

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High-pressure pseudotachylytes as field evidence for lower crustal seismicity

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Seismic records show earthquakes in lower crustal levels in almost all collisional orogens, even though rocks are generally predicted to flow rather than fracture under these conditions. The experimentally determined creep flow law of quartz is used for most rheological models of the continental crust, since it is one of the most abundant mineral. In the typical “Christmas-tree” representation of lithospheric strength, the intersection between the line representing Mohr-Coulomb fracture and the experimental curve for power-law viscous flow of wet quartz occurs around 250-280°C, consistent with field observation that the transition to crystal-plastic flow in quartz starts around such temperatures.

The Musgrave Ranges in Central Australia expose sub-eclogitic facies shear zones of Petermann age (~ 550 Ma), overprinting granulites of Musgravian age (1.2 Ga). The distribution of deformation is very heterogeneous and all large-scale shear zones are associated with pseudotachylyte (pst). Since pst is thought to form by seismic-slip induced frictional melting, it can be used as an indicator of fossil seismogenic fault zones. Pst is identified in the field by the presence of injection veins, breccias, crosscutting relationships and their fine grain size. Observed pst is often not black and glassy as reported from many classic low-grade examples, but shows a caramel color and a well-developed foliation and a lineation, often parallel to the mylonitic fabric. Neocrystallized garnet and clinopyroxene with grain sizes of less than 5 µm have grown inside the pseudotachylyte veins. Geothermobarometric calculations based on microprobe analyses give temperatures around 650 °C and pressure around 1.2 GPa, identical to the conditions of deformation in the associated ductile shear zones. Evidence for cyclic development of both brittle and ductile structures is provided by sheared pst-breccias, which incorporate clasts of an older generation of sheared pseudotachylytes and by sheared pst crosscut by undeformed pst veins. Pst-veins also often act as a precursor structure for localized shear zones, as seen in low strain domains. Here, pst-veins are sheared and form mm-wide but 10’s of meters-long localized shear zones in little deformed host-rock. In contrast, quartz veins with the same orientation did not localize shearing and are folded or boudinaged. This presumably reflects the “dry” deformation conditions, with generally no new growth of hydrous minerals or evidence for introduction of hydrous fluids. Shearing has preferentially localized on precursor fractures and fine grained pst rather than on compositional inhomogeneities.

The relationship between the Vizcaíno ‘composite’ Terrane and the ‘Antimonio Terrane’ during the Upper Triassic

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The North American Cordillera, from Alaska in the north to Mexico in the south, consists of several terranes that have a doubtful paleogeography (e.g. Coney et al. 1980). The major reason for this circumstance is, that the outcrop-situation for the time interval of the Upper Triassic is difficult. On the base of todays reconstructions for paleogeography, and tectonic history of the Cordillera, two potential terranes with shallow-water carbonates of Norian age were selected. These terranes are the “Antimonio Terrane” (Sonora, Mexico), and the Vizcaíno ‘composite’ Terrane (Baja California Sur, Mexico) (fig. 1).

During field trips in 2012, and 2014, samples for the comparison of litho-, and microfacies of the two localities were collected.

With this study we try to prove a proximal relationship between the Antimonio, and Vizcaíno areas, allowing us to reconstruct these two potential terranes as a single “joint terrane” environment. Furthermore we want to compare these two localities with the previously-investigated Wallowa terrane in the Blue Mountain Province (Oregon, USA), also containing Upper Triassic shallow water carbonates.
The Upper Triassic succession of the Antimonio Terrane consists of shallow-marine sediments (González-León, 1997), whereas the deposits of the Vizcaíno ‘composite’ Terrane near the village of San Hipólito represent slope to deeper marine environments (Orchard et al. 2007). In Sonora, we found limestones, calcareous siltstones, and fine grained sandstones. The first two lithologies contain shallow-water fossil assemblages that include chambered sponges, and scleractinain corals. Near San Hipólito deepwater limestone, chert, a limestone breccia, and sandstone crop out. The Norian-dated clasts of the breccia contain shallow-water fossils. In particular the sponges, and corals show strong affinities to the fossils observed in the Antimonio area.

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P 1.12

Shear stress and seismic cycle length of SAF at Parkfield

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With regular ruptures identified since more than 2000 years on a same fault segment the Parkfield mainshock sequence is probably one of the best earthquake sequence ever documented. The magnitude Mw6 earthquake in 1966 and the subsequent prediction of a following mainshock in 1988 +/- 5 years triggered the deployment of a dense geophysical network to monitor the central San Andreas Fault (SAF) near Parkfield, California. However, no mainshock occurred until September 2004, i.e. years after its prediction date. In addition to the incorrect forecast, the 2004 earthquake differed from the previous M6 mainshocks that occurred in 1922, 1934, and 1966, by the location of its hypocenter near the southern end of the fault segment, and its rupture propagation from south to north. Here, we show that both time delay and location of the 2004 hypocenter can be explained by static stress changes imposed by regional (i.e., within 100km) and local seismic activity (M>4) on the SAF in the vicinity of Parkfield. Our results suggest that the critical stress level leading to a mainshock is sensitive to shear stress disturbances, and has been constant since 1901. At last, we quantify that the interseismic slip rate along the SAF at Parkfield is ~ 14.3±4.6 mm/yr.

P 1.13

Impact of elasticity on lithospheric shear localization

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Lithospheric shear localization plays a fundamental role during the initiation of subduction zones, during the formation of extensional detachment zones and during the evolution of convergent orogens. However, the physical processes responsible for shear localization, such as shear heating or grain size reduction, and their relative importance for shear localization are until now incompletely understood. To better understand shear localization due to shear heating, we perform two dimensional (2-D) numerical simulations of lithospheric shortening. The numerical simulations are based on the finite element method using the mesh generator Triangle and the solver Milamin. Our model configuration consists of a lithosphere composed of an upper crust, a lower crust and a mantle. The rheology for each unit is a combination of experimentally derived flows for diffusion and dislocation creep. Two systematic series of simulations quantify the impact of the basal temperature and the shortening strain rate on the shear localization: in one series a visco-elasto-plastic rheology is applied and in the other series a visco-plastic rheology is applied to quantify the impact of elasticity on the shear localization.

The results show three general types of deformation for both series depending mainly on the shortening strain rate: 1) thickening (pure shear) dominated deformation, 2) folding dominated deformation and 3) shear localization dominated deformation. The visco-elasto-plastic models show a much stronger localization than the visco-plastic model. The impact of the elasticity will be quantified and implications for lithospheric deformation will be discussed.
P 1.14

The Neo-Tethyan subduction zone(s,?) in Azerbaijan, NW Iran: preliminary results

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Azerbaijan in NW Iran, and in particular the Khoy ophiolitic complex, are relatively ill documented elements of the Alpine-Himalayan orogenic belt. They are attributed to multiple accretion and continental collision after subduction and closure of the Tethys Ocean and related seaways. We are interested in the pre- to syn-collisional relationships between the ophiolitic, arc and other magmatic units. This work investigates to what extent single or multiple collisions and orogeny have shaped the NW Iranian Plateau. In particular, we want to understand the changes in deformation style within the collision zone and the effects of several possibly coeval events such as closure of two suture zones separated by an arc and possibly followed by slab break-off(s). Aster satellite images and published geological maps provide fundamental background knowledge. New fieldwork focused on sampling the different magmatic rock units to specify the structural record and the structural relationships between the various lithological units. Cretaceous to Quaternary, regionally distributed magmatic rocks were collected to have good resolution of their changes in space and time. Petrological, geochemical and isotope studies characterize magmatic rocks and their sources. Fossil-bearing sediments provide stratigraphic ages of important contacts. Major and trace element geochemistry of mantle and crustal suites of the Khoy ophiolitic complex constrain their tectonic setting. Two complexes were defined on the basis of K-Ar dating (Khalatbari-Jafari et al., 2004). An older, probably subducted ophiolite of Triassic-Jurassic age and a younger non-metamorphic ophiolite of Late Cretaceous age. Previous work suggested that the basaltic lavas of the Khoy ophiolitic complex were created at an oceanic spreading centre. Structural data document a dominant top to the SW thrusting of an imbricate zone with stacked thrust sheets in a duplex system. Active faults, dominantly normal and strike-slip faults document current SSW-NNE compression, consistent with GPS and seismotectonic information.

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P 1.15

Salt dissolution in the underground of Switzerland, especially in the canton of Fribourg

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Within the Triassic system of the non-Alpine part of Switzerland there are two salt formations, the Muschelkalk and the Gipskeuper. The geographical extent of the two formations is shown by Jordan (2008). The Muschelkalk salt is widespread from the North Sea to northwestern Switzerland where it is exploited by solution mining. Hauber (1993) describes three separate Swiss salt basins, Schweizerhall-Ergolz, Rheinfelden, and Zurzach. The discussion is still open if these three basins were originally discontinuous or secondarily separated by salt dissolution (also called subrosion). Detailed investigations reveal several zones of „breccia” which may in fact be dissolution residues (the salt becoming raw material for the younger Gipskeuper formation ?). The Gipskeuper, the second salt formation of non-Alpine Switzerland, has a similar extent as the Muschelkalk salt. The thickness of both salt formations is difficult to establish because they were transformed into decollement planes of the Jura foldbelt.

Shapes of salt dissolution: If and when water undersaturated in NaCl reaches a salt formation it will start to dissolve it. This may occur from above, laterally, or from below (volcanism). Once started it will usually lead to increasing permeability and to an expansion of the leached volume. The void will be filled by residual sediments and collapse material and then expand laterally, perhaps forming a pear-shaped collapse zone. Eventually, the stalk of the pear will reach the surface and form a small diameter sinkhole. With more salt leached away more surface sediments will be collected. In the long run extensive subrosion basins may develop, having slopes several kilometer wide, the so-called salt slopes.

Canton of Fribourg: On the website www.bfe.admin.ch/dokumentation/publikationen/index.html you can find the report „Sicherheitsbericht Rahmenbewilligungsgesuch Ersatz Kernkraftwerk Mühleberg”. This report contains several reflection seismogrammes, for ex. FR.S750010. Its interpreted southwestern portion shows a more or less flat lying sequence of 4 horizons, from base Mesozoic to base Tertiary. Interpreting an additional horizon, near top Triassic, we find a travel time for the Triassic interval of about 150 msec, possibly 250 m thickness. Proceeding northeastward, at geophone point 620, the whole series bends down, even the Quaternary surface beds (max. at GP 760). Between GP 760 and 860 the interval in question has a TWT of 30 msec, perhaps 50 m. From this minute seismogramme we arrive at a rough guess that 200 m salt have been dissolved in its central part. Combining this interpretation with the tectonic map included in the above report one may say “The Fribourg structure is a N-S trending salt dissolution basin promoted by several N-S trending faults”. The alignment of seismic epicentres on its western flank is the presently active dissolution front. The Swiss Seismological Service calculates the epicentre depth at about 2 km which is in full agreement with the reflection seismic interpretation. There are further small sinkholes on FR.S750010.

The Creux du Van, canton of Neuchâtel, is the most surprising morphological feature of the Jura foldbelt. In a way it is similar to an amphitheatre. To my knowledge until now its erosion has been explained by river and/or glacial forces. As an alternative a salt sinkhole explanation is proposed, affecting Triassic salt at approximately 3 to 4 km depth. Seismic section 11 (Sommaruga 1997) close by shows a complex structure. Further seismic investigation is almost impossible due to the abrupt morphology.

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The Water Circulation In The Fractured Rock: The Role Of Stylolites In The Development Of Karst

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Karst development is strongly influenced by the tectonic deformation of the area where they occur. This is because, the structure of the rock mass in which it occurs (e.g., lithology, primary porosity, environmental conditions, etc.) affects the water circulation, thereby affecting permeability and porosity. Traditionally, in the field of karstology, it is maintained that water circulation is essentially related to extensional structures which, it is assumed, are more favorable to water circulation. In fact, the permeability of the fault zone is sufficiently high only in the early stages of the movement, because after a short period the deposition of minerals (e.g., calcite) coming from these same fluids reduces its porosity/permeability. Fault zones and fractures play an important role in fluid circulation, acting as permeability barriers or conductors, depending on the specific conditions (lithological and structural in particular), and on the distribution of other structures associated with them. Therefore, structural analysis can provide both qualitative and quantitative assessments of the relationship between structure and fluid circulation and allow us to determine whether a fault zone acts as a barrier or as a hydraulic conductor (Caine 1996).

The stylolites (Rawling 2001), structure associated with the faults play an important role in the fluid circulation and in particular in the development of the karst. In this study, conducted in the karst area of Fasano it was verified that the karst tends to develop along tectonic stylolites formed by compression.

In the study area tectonic stylolites (fig.1) are shown to be the favoured structures for initiating the development of both, underground and epigean karsts.

Figure.1. Starting from the top: scanline; distribution of fracturing (joints and stylolites); distribution of karst; distribution of stylolites

The analysis performed (structural, XRD, on permeability) are allowing us to take the first considerations on the importance of stylolites in the development of karst (fig.2)

The aquifers represent about 40% of sources of drinking water and their importance will increase in coming years due to the progressive deterioration of the quantity and quality of groundwater as a result of phenomena exploitation and pollution. Therefore, the future water supply will be increasingly dependent on these sources, so the importance of these studies

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Figure 2. The karst is mainly present along the surfaces of tectonic stylolites. It is possible to observe the evolution of a stylolite.
Field Constraints on the Rheology of Quartz in “Wet” or “Dry” Middle to Lower Continental Crust

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Quartz is an abundant mineral in most rocks of the continental crust and is generally considered to be the main load-bearing component determining the viscous rheology of the middle to lower crust. However, it has long been known from laboratory experiments that quartz rheology is strongly influenced by the amount of water—“wet” quartz is very difficult to deform crystal-plastically. Here we present direct field evidence for the markedly different behaviour of quartz under “wet” and “dry” conditions, on the corresponding differences in response to deformation of the middle to lower crust, and implicitly on the markedly different overall strength of the crust. We compare and contrast the behaviour using examples from the Tauern Window (Eastern Alps), the Simplon Fault Zone (Central Alps), the Adamello (Southern Alps) and Sierra Nevada (western USA) batholiths (all “wet”) and the Mont Mary (Central Alps), Ivrea Zone (Southern Alps) and Musgrave Ranges (Central Australia) (all “dry”). The temperature conditions for these areas largely overlap and correspond to those present at middle to lower crustal levels.

Typical of “wet” conditions is that new quartz veins develop during deformation, whereas under “dry” conditions only older precursor veins are present. Under “wet” conditions, quartz veins and quartz-rich layers are weaker than the surrounding more quartzo-feldspathic gneisses or biotite-bearing granitoids and strongly localize shearing, typically developing a mylonitic fabric. In examples from the Tauern Windows metagranitoids, quartz is even weaker than large calcite crystals, which form porphyroclasts within the quartz mylonites. The interpreted shear flow stress in these examples is only on the order of 10 MPa or less (Mancktelow & Pennacchioni, 2010). Under the ambient upper amphibolite facies conditions (ca. 550°C), quartz recrystallizes by Grain Boundary Migration (GBM) and exaggerated grain growth leads to average grain sizes on the scale of many 100’s of μm up to mm size. The strong CPO developed at moderate to high shear strain shows a point maximum of c-axes parallel to the intermediate Y fabric axis, consistent with a dominant prism <a> slip system. Directly comparable microstructures and CPO are observed for quartz veins deformed under similar conditions in the Simplon Fault Zone and during cooling of granitoid batholiths of Adamello and the Sierra Nevada (e.g. Pennacchioni et al. 2010). Under the Scanning Electron Microscope (SEM), secondary electron (SE) images of broken sample surfaces of quartz mylonites show a significant porosity and in some locations open space and coherent crystal faces along grain boundaries. Although shearing localizes both on compositional layers (e.g. quartz veins) and precursor fractures, generally no pseudotachlyte is observed associated with this localized shearing under “wet” conditions.

In marked contrast, under similar P-T but “dry” conditions (e.g. Ivrea, Musgrave Ranges), quartz veins or layers do not localize strain and shear is only localized on precursor fractures that largely ignore compositional layering. In the Musgrave Ranges, the one exception is that older finer-grained dolerite dykes do heterogeneously localize both pseudotachlyte formation and ductile shearing, especially towards the finer grained (“chilled”) dyke margins. Recrystallization of quartz within shear zones is by Subgrain Rotation (SGR) and grain sizes are on the scale of many 10’s of μm or less (Mancktelow & Pennacchioni, 2010). Under the ambient upper amphibolite facies conditions (ca. 550°C), quartz recrystallizes by Grain Boundary Migration (GBM) and exaggerated grain growth leads to average grain sizes on the scale of many 100’s of μm up to mm size. The strong CPO developed at moderate to high shear strain shows a point maximum of c-axes parallel to the intermediate Y fabric axis, consistent with a dominant prism <a> slip system. Directly comparable microstructures and CPO are observed for quartz veins deformed under similar conditions in the Simplon Fault Zone and during cooling of granitoid batholiths of Adamello and the Sierra Nevada (e.g. Pennacchioni et al. 2010). Under the Scanning Electron Microscope (SEM), secondary electron (SE) images of broken sample surfaces of quartz mylonites show a significant porosity and in some locations open space and coherent crystal faces along grain boundaries. Although shearing localizes both on compositional layers (e.g. quartz veins) and precursor fractures, generally no pseudotachlyte is observed associated with this localized shearing under “wet” conditions.

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P 1.18

Tectonics between the Préalpes Klippen and the swiss western Molasse Basin in the Bulle region (Fribourg)

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The area of Bulle is located in the frontal part of the allochthonous Préalpes Klippen belt of western Switzerland, between SE-dipping imbricates of the Subalpine Molasse to the North and the overriding Préalpes Médianes to the South. The Bulle area is structured by two major tectonic elements: [i] a NE-SW trending, SE-dipping thrust system affecting the Subalpine Molasse unit and the Préalpes Klippen belt, [ii] a N-S trending subvertical strike-slip fault system. The thrust system encompasses very large tectonic slivers of Ultrahelvetic origin (to the SE and to the E) considered to be part of a tectonic “mélange” (Mélange infrapréalpin) associated with the basal detachment of the Préalpes Klippen; a series of tectonic slivers made of Gurnigel nappe sediments belonging to the Préalpes klippen belt, and the Subalpine Molasse. These different structural elements have a general NE-SW trend but are also juxtaposed in an E-W direction. This latter situation is due to the topographic incision of the S-N flowing Sarine river and the former Sarine glacier and results in a situation where the Subalpine Molasse unit is apparently almost in direct contact with the base of the Préalpes Médianes. Some authors have interpreted this arrangement as structural high associated with N-S left-lateral strike-slip faults forming a regional flower structure.

Interestingly the Ultrahelvetic tectonic slice bordering the city of Bulle to south, which is part of the Mélange infrapréalpin and which is sitting in the center of the “structural high”, is made of series of lower Jurassic age only, whereas the more important tectonic sliver east of Lake Gruyère is made of series mostly younger, suggesting the possibility of E-W decoupling.

On the recent geological atlas of Switzerland, the 1:25’000 scale map of Gruyères, the faults of the eastern border of the structural high extend into the Sarine river valley to the South. The Sarine valley is a broad syncline where the Cretaceous series of the Préalpes médianes are exposed. This implies that in this region the basal thrust of the Préalpes Klippen is locally deeper by around 1 km than elsewhere in the Préalpes Klippen.

We thus would have in a N-S direction a juxtaposition along the same fault system of a structural high and a depression. We use a combination of surface data, information from boreholes in the vicinity and seismic surveys to propose a new NW-SE trending cross-section from the Plateau Molasse unit of the western Molasse Basin across the Subalpine Molasse unit into the Préalpes Klippen. The section will extend down to top basement which in the vicinity is characterized by a structural high known from seismic surveys and also from seismic tomography (See Abstract Abednego et al.). Our alternative structural model of the area will rely on structural topography, including basement inversion, to explain the important changes in basal décollement depth and structural style and possibly related to strain partitioning between a NW-SE direction of shortening and a NE-SW extension-related to shearing.


Palaeosoils stacking patterns as a tool for unravelling the subsurface architecture of mud-rich fluvial reservoirs.

Andrea Moscariello and Branimir Šegvić

In the subsurface, robust well correlation represents the starting point in order to understand the architectural framework of any reservoir rock. Especially in mud-rich continental barren sequences, characterised by scarce occurrence of sandstone beds, correlation may result a difficult task. In this type of depositional environment correlation techniques based on bio- or chemo-stratigraphic analyses have been successfully applied to identify discrete chronostratigraphic units which generally may represent 3rd or 4th order stratigraphic changes in response to either tectonic (e.g. increased erosion and sediment supply, changes in provenance) or climatic changes (e.g. weathering processes in the catchment, changes in erosion and sediment supply) or, in most cases, both.

Yet, when sand bodies in the subsurface are thought to be narrower than the actual well spacing, the correlation between them is becoming a challenge and more detailed information are then required to outline better the internal reservoir architecture and identify channel distribution.

Detailed insights on reservoir anatomy have been provided by the study of palaeosols. Their different types (pedofacies) and vertical trends can directly be related to different aggradation rates and in turn proximity to channel belt. Ultimately this can provide useful information on the overall stratigraphic pattern and sand connectivity within the fluvial reservoir.

Different pedofacies signatures, as a function of their maturity (e.g. peds development, rootlets and nodules distribution, degree of preservation of primary sedimentary structures) can be identified both on core and logs and a different range of pedofacies types can be identified (usually 2 to 4).

Pedofacies composition highlighted by both standard petrographic microscopy and QEMSCAN automated mineralogy reflects the time of subaerial exposure and the pedologic processes (bioturbation and mineralisation) occurred during the soil formation. The presence of different stage of maturity in paleosoils can be also highlighted by shear sonic logs which may respond to the different degree of vertical discontinuities in the rock associated with paleosoils development (peds).

In general a highly mature paleosoils suggest very low aggradation rates of new sediments and hence a large distance from active channel belts or a temporary stop/decrease in sediment supply (e.g. no overbank deposition due to dry period or reduced water discharge). The staking pattern of these pedofacies can therefore unravel the avulsive and aggradational character of a river system. The study of several wells in a study area can unravel lateral changes in fluvial aggradational style within each chronostratigraphic zone (based on bio or chemo-stratigraphy) and therefore indicate large scale architectural changes at reservoir scale. The systematic mineralogical study of these pedofacies, with automated mineralogical techniques can help to unravel important changes in provenance or autogenic components throughout the stratigraphic record and thus help discriminating the tectonic vs. climatic signature recorded by the sedimentary succession.
Fig. 1: A) Vertical sequences of pedofacies as recognised in core showing a vertical succession from 1 to 4 passing gradually form 2 and 3, the pedofacies 4 being the most mature and displaying clear peds structures. Top of core is in the top left of the picture. B) vertical succession of pedofacies in mud-rich fluvial reservoirs showing the sharp changes from pedofacies 4 to 1 suggesting a strong periodicity in the avulsive fluvial system which temporarily allowed the abandonment of flood plain and the development of mature paleosoils. C) QEMSCAN images of four types of pedofacies as indicated in each image.
LA-ICP/MS U-Pb zircon ages of porphyritic dykes from the Sesia-derived Insubric mylonite belt (Piemonte/Ticino)

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Along its central segment between Lago Maggiore and Valle d’Ossola, the Insubric fault is the southern boundary of the structural and metamorphic Lepontine dome which was uplifted with respect to the Southern Alps by about 20 km (Trümpy 1980). The horizontal displacement of the Insubric fault amounts to at least some tens of kilometres (e.g. Ahrendt 1980). The uplift amount decreases towards east and west as the eastern and western boundaries of the Lepontine dome turn away from the Insubric fault while the horizontal displacement amount increases eastward. These variations in horizontal and vertical displacement amounts are at least partly accommodated by fault branching off the Insubric fault (e.g. Handy et al. 2005) and the Insubric fault itself comprises several mylonite belts with different kinematics (e.g. Schmid et al. 1987, 1989). Between Lago Maggiore and Valle d’Ossola, the Insubric fault consists of two several hundred metres wide greenschist-facies mylonitic belts, a northern one (belt 1) with thrust kinematics in its present orientation, and a southern one (belt 2) with combined dextral and minor normal-fault kinematics (Schmid et al. 1987). Belt 1 affects the internal (southern) part of the Penninic Sesia zone and belt 2 the external (northern) part of the South Alpine Ivrea zone and/or sporadically intervening slivers of the Canavese zone.

Early Oligocene Alpine magmatism was spatially and temporally related to the Insubric fault (e.g. Rosenberg 2004). Greenschist-facies metamorphism in belt 1 was retrograde with respect to amphibolite-facies Lepontine regional metamorphism, dating of magmatic rocks with high-retentivity isotopic chronometers is the only possible way to constrain the onset of belt 1 shearing because dating of synkinematic minerals with low-retentivity isotopic chronometers generally yields cooling ages (e.g. Hurford 1986; Schmid et al. 1989; Steck and Hunziker 1994). LA-ICP-MS U-Pb zircon age dating of porphyritic dykes yielded concordant ages of 32.78±0.18 Ma and 32.75±0.16 Ma for oscillatory zoned rims. We therefore interpret these ages as magmatic emplacement ages. Ages of 287.7±1.0 Ma and 280.9±1.9 Ma (all errors are 95 % c.f) from inherited magmatic zircon cores additionally testify to an Early Permian magmatic stage.

The porphyritic veins are affected by belt 1 shearing to variable degree. Microtextural evidence shows that this shearing occurred exclusively under solid-state conditions and, therefore, the Early Oligocene ages provide a maximum time constraint for the onset of Insubric mylonitisation. While farther east the Insubric fault is immediately paralleled to the north by higher-grade amphibolite-facies, partly syn-magmatic Oligocene shearing in the Southern Steep Belt, this higher grade shear zone is clearly separated from Insubric mylonite belt 1 by the intervening Sesia zone in our study area.

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P 1.21
Late Cretaceous-to-Pliocene thermo-tectonic history of Pelagonia (northern Greece) from zircon and apatite fission-track ages

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The Pelagonian zone, between the External Hellenides/Cyclades to the west and the Axios/Vardar/Almopia (AVA) zone and Rhodope to the east, was involved in the late Early Cretaceous and in the Late Cretaceous-Eocene compressional events. Timing and spatial distribution of these events have remained so far partly unresolved. We will present new and published zircon (ZFT) and apatite (AFT) fission-track ages integrated with new field observations to constrain their thermal overprint.

The Early Cretaceous (130-110 Ma) thrust system of the Pelagonian basement and AVA zone was covered on a 99-to-80 Ma unconformity by marine sediments, whose deposition continued until ca. 66 Ma (documented by Globotruncanae). The metamorphic imbricates of the western AVA zone cooled below 240 °C between 102 and 93.5-90 Ma and the ones of northern Pelagonia, eastern AVA zone and western Rhodope between 80 and ca. 68 Ma. This regional ca. 30 Ma long cooling and subsidence was followed by the reactivation of thrusting that caused abrupt and rapid cooling and erosion of the Pelagonian basement at ca. 68 Ma, as documented by clasts in ca. 66 Ma old marine sediments with detrital ZFT ages clustering at ca. 68 Ma. In the Paleocene-Eocene thrusting migrated in the External Hellenides and cooled western Pelagonia below ca. 120 °C in the hanging wall of its sole thrust. Subsequently in central-eastern Pelagonia, ZFT and AFT ages attested rapid and uniform cooling between 24 and 16 Ma in the footwall of a major extensional fault. Extension started even earlier at 32.7 Ma in the western AVA zone according to reset AFT ages within normal faults. A final post-7 Ma rapid cooling is inferred by inverse modeling of AFT lengths along a E-W normal fault zone cutting Pliocene-to-recent sediments.

P 1.22
3D visualization of the structures at Grimsel Test Site GTS and their link with sampled groundwaters

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We present preliminary results from a research project aiming at the development of structural and hydrochemical models in the Grimsel region. For the last 30 years, numerous experiments and research investigations in the Grimsel Test Site (GTS) delivered a vast number of structural, physical and geochemical data (e.g. Keusen et al. 1989). In the context of the present study, the natural fluid flow pathes are investigated in 3D space by a combination of 3D structural modelling and geochemical approaches incorporating groundwater inflow rates and geochemistry. For this purpose, a 3D structural model will be developed in a first step, which links structures at the level of the GTS tunnels with the topographic surface. Information compiled from previous studies are combined with newly acquired tunnel and surface mappings. The subsequent structural 3D visualization of the geometry is performed with the Move™ software (from Midland Valley Exploration Ltd).

To investigate the groundwater pathways and their relation to the structural domains, samples have been taken at regular time intervals from different borehole locations in variably deformed granitoid rocks, shear zones, meta-basic dykes. In-line measurements of pH, Eh and conductivity confirmed the previously observed low mineralisation of GTS groundwater (Frick et al 1992). The main cations and anions as well as the δ¹⁸O and δ²H are quantitatively analysed. A compilation of historic data (water chemistry, inflow rates, hydraulic heads, transmissivities, limited natural tracers) and a comparison with the present data is ongoing. First results of both 3D modelling and geochemical analyses will be presented in this presentation.
P 1.23

Dating low grade deformation of the Patagonian fold-and-thrust belt in the Torres del Paine area, Chile 51° 30’S: first results

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K/Ar dating on syn-kinematically formed illites has been used to date different deformation phases triggered by the subduction of the Antarctic plate beneath the South American plate, resulting in the formation of the Patagonian retro-arc fold-and-thrust belt.

The Cretaceous to Neogene Patagonian east-vergent fold-and-thrust belt in southern Chile consists of a >4000 m thick sequence of turbidites, sandstones and shales which were deposited in a basin structure formed throughout the Late Jurassic breakup of Gondwana. The kinematic evolution of the fold-and-thrust belt has been roughly defined by six different deformation stages of foreland shortening between the Late Cretaceous and the Neogene (Fosdick et al 2011).

Clay rich samples were selected within the Cretaceous Punta Barrosa and overlying Cerro Torro Formation south of the Torres del Paine Intrusion. Illite crystallinities of the <0.2 µm and <2 µm clay mineral size fractions were determined and range from 0.23 to 0.58°2θ in the <0.2 µm and 0.28 to 0.46°2θ in the <2 µm fraction. Diagenetic values are observed in the East, where deformation was less intense. The alignment of illite crystallinity values seems to correlate best with the regional folding.

A carefully selected suite of <0.2 µm and <2 µm clay mineral size fractions has been subjected to K/Ar age dating to establish time constraints on the deformation stages of the fold-and-thrust belt. K-Ar ages vary between 46.2±0.7 and 62.1±0.1 Ma in the <0.2 µm fraction and between 55.3±0.9 and 80.8±1.2 Ma in the <2 µm fraction. Thus, the folding initiated at around 60 Ma and continued until 46 Ma in the westernmost part of the study area. In the East, ages of the <2 µm fraction indicate stratigraphic ages (80 Ma) and are therefore, not affected by deformation events. Furthermore, the age data indicate both, a continuous regression of deformation intensity and a regional low-grade metamorphic overprint from west to east related to deformational shortening. Based on this preliminary data any influence by the intrusive Torres del Paine Complex can be excluded.

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**P 1.24**

**Influence of Melting on the Long-Term Thermo-Chemical Evolution of Earth’s Deep Mantle**

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Melting has always played a key role in Earth evolution. Early solidification of a magma ocean may have left the mantle compositionally stratified and may have continued in the form of a long-lived basal magma ocean (BMO). Ongoing upper mantle/transition zone melting, perhaps associated with water and carbonate, may have caused ‘internal differentiation’, resulting in dense enriched products that sink. Throughout Earth’s history melting in the shallow mantle has produced crust, most of which was recycled into the interior and some of which may have segregated above the core-mantle boundary, joining possible enriched products from early differentiation, internal differentiation and BMO solidification to produce a Basal Melange (BAM). Here we investigate the thermal and chemical evolution of Earth’s interior from the ~molten state to billions of years later using global-scale numerical simulation. Our previously-published models that included only oceanic crustal production and recycling (e.g. Nakagawa & Tackley, 2014) indicated that (i) a layer of subducted crust can rapidly build up above the CMB, (ii) early-formed layering above the CMB may have been necessary to avoid rapid early core cooling and a too-large present-day inner core, (iii) magmatism is the dominant heat transport mechanism early on, (iv) melting acts as a thermostat, buffering mantle temperature. Here we improve the models to handle deep melting including melt fractions of up to 100%, fractional melting using a eutectic model, segregation of melt and solid, and a parameterized magma ocean treatment at high melt fractions (using an eddy diffusivity based on mixing length theory, similar to previous 1-D treatments). We investigate and characterize the evolution of deep mantle structure in the limits of negatively buoyant melt and positively buoyant melt. We focus on the interplay of deep melting and melt migration, primordial layering, recycled crust and harzburgite, and products of upper mantle internal differentiation, in producing a heterogeneous deep mantle.

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**P 1.25**

**Unravelling tectonics and surface processes in exhumation history of South Alaska: insights from the thermochronological record**

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The southern Alaska range presents an ideal setting to study complex interactions between tectonics, climate and surface processes in landscape evolution [e.g. Champagnac et al., 2012]. It exhibits active tectonics with the ongoing of subduction/collision between Pacific and North America, and major active seismogenic reverse and strike-slip faults [Meigs et al., 2008; Chapman et al., 2012]. The alpine landscape, rugged topography and the important present-day ice-coverage reveal a strong glacial imprint associated with high erosion and sediment transport rates [Berger et al., 2008]. Therefore, the relative importance of glacial erosion and tectonics for the observed late-exhumation history appears to be quite complex to decipher.
Here, we first perform a formal inversion [Herman et al., 2013; Fox et al., 2014] of an extensive bedrock thermochronological dataset collected in southern Alaska over the last decades to quantify the large-scale 20-Myr exhumation history. We show that almost half of the variability within the thermochronological record can be explained by modern annual precipitation spatial distribution, the residuals clearly evidencing localized exhumation along major tectonic structures of the frontal fold and thrust belt [Enkelmann et al., 2009; Spotila and Berger, 2010; Enkelmann et al., 2014]. Our results confirm high exhumation rates in the St Elias “syntaxis” and frontal fold and thrust belts for the last 0-2 Myr, where major ice fields and high precipitation rates likely promoted high erosion rates; the impact of late Cenozoic glaciations impact being less visible there than in less active mid-latitude mountain ranges such as the European Alps or British Columbia [e.g. Shuster et al., 2005; Valla et al., 2011]. On the contrary, our inversion outcomes highlight that north of the Bagley Icefield long-term exhumation has remained quite slow and continuous over the last ~20 Myr [e.g. Spotila and Berger, 2010; Enkelmann et al., 2010], with no late-stage signal of exhumation change since the onset of glaciations depiste clear glacial imprint in the landscape.

To overcome this potential bias in resolving the tectonic and glacial impact on exhumation history, we focus on the Granite Range (Wrangell-St Elias National Park, Alaska), an area presenting a strong glacial imprint but minor tectonic activity with only localized brittle deformation. We sampled four elevation profiles over an East-West transect for low-temperature thermochrometry. Apatite (U-Th-Sm)/He dating provides ages between ~10 and 30 Ma, in agreement with published data [Spotila and Berger, 2010; Enkelmann et al., 2010], and shows apparent low long-term exhumation rates (~0.1 km/Myr). 4He/3He thermochronometry on a subset of samples reveals a more complex exhumation history, with a significant increase in exhumation/erosion since ~6-4 Ma that we relate to the early onset of glaciations and glacial erosion processes. Our results, in agreement with offshore sediment records [Rea and Snoeckx, 1995; Reece et al., 2011], thus confirm early glacial activity and associated erosion response in Alaska, well before the onset of Pliocene-Pleistocene Northern Hemisphere glaciations.

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**P 1.26**

**3D FEM modelling of fold nappe formation and the Rawil depression in western Switzerland**

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The Rawil depression is an axial depression located in Western Switzerland around the border between the cantons of Bern and Vallais. It is characterized by an opposite plunge of fold-axes in the Helvetic nappe system as well as the underlying basement. The fold axes of the Morcles fold nappes in the west of the Rawil depression plunge to the ENE whereas the fold axes in the more eastern Doldenhorn nappe plunges to the WSW. The Morcles nappe is mainly the result of layer parallel contraction and shearing (Ramsay, 1981). During the compression the massive limestones were more competent than the surrounding marls and shales, which led to the buckling characteristics of the Morcles nappe, especially in the north-dipping normal limb. The Doldenhorn nappe exhibits only a minor overturned fold limb and shows significantly more localized deformation at its base (Steck et al., 1999). A possible explanation for this stronger localization at the base is that the weak basal sediments in the half graben deposits forming now the Doldenhorn nappe have been thinner than the sediments in the half graben sediments forming the Morcles nappe (Pfiffner, 2011). The Morcles nappe is tectonically separated from the more eastern Doldenhorn nappe due to the Rawil depression. The Helvetic nappe stack consists of the Morcles nappe in the west and Doldenhorn nappe in the East (both nappes are in the infrahelvetic domain) as well as the overlying Wildhorn and Diablerets nappes. In the Rawil depression the nappe stack is overprinted by a dextral transtension. In the deepest part of the depression, where the highest nappes are preserved, oblique normal faults with significant displacement are observed (Gasser and Mancktelow, 2010). The evolution during exhumation and cooling from ductile to brittle deformation is documented in this area where ductile folding led to the axial depression and brittle faulting led to the normal faults (grlabs). The sediments of the Helvetic domain are a repetition of limestones, marls, shales and sandstones which were deposited from late Triassic to Early Oligocene at the European margin (Escher et al., 1993). After the last sedimentation the Helvetic nappes were progressively formed by folding and overthrusting. The lowermost nappes, the Morcles and Doldenhorn nappes are autochthonous and paraautochthonous, whereas the overlying Wildhorn nappe, Diablerets nappe and Gellihorn nappe are detached from their basement. The future Helvetic nappes represented the distal margin of Europe north of the Valais domain. After the nappe stacking due to compression, the Helvetic nappe stack was folded and updomed due to continuous compression. This led to the exhumation of the external massifs.

The geometry and structures around the Rawil depression are relatively well documented and described. However, the fundamental dynamics of the formation of the large-scale 3-D structure including the Morcles and Doldenhorn nappes and the related Rawil depression is still incompletely understood. Therefore, we perform simple 3-D numerical simulations to better understand the dynamics of fold nappe formation with laterally varying initial geometry. Such simulations require a numerical algorithm that can accurately track material interfaces for large differences in material properties (e.g. between limestone and shale) and for large deformations.

We will present 2-D and 3-D numerical simulations using a finite element (FE) algorithm for large strain deformation of power-law viscous material. The simulations are applied to the formation of tectonic fold nappes as the Morcles and Doldenhorn nappes and to the later formation of the Rawil depression.

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Interplay between seismic fracturing and aseismic creep during strain localization in the middle crust (Woodroffe Thrust, Central Australia)

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The Musgrave Ranges in Central Australia provide an excellent exposure of the shallowly south-dipping Woodroffe Thrust, which placed $\sim$1200 Ma granulites onto similarly-aged amphibolite and granulite facies gneisses. This $\sim$ 400 km long E-W structure developed under mid-crustal conditions during the intracratonic Petermann Orogeny around 550 Ma (Maboko et al., 1992; Camacho and McDougall, 2000). From field observations, the shortening direction is constrained to vary between NNE-SSW and NNW-SSE and the sense of movement is consistently top-to-north thrusting. Ductile deformation along the Woodroffe Thrust almost entirely localized in the footwall rocks, developing a zone of protomylonites, mylonites, ultramylonites and sheared pseudotachylytes, several hundreds of metres wide, with pseudotachylyte abundance and the degree of mylonitization rapidly decreasing further into the footwall. In contrast, the immediate hanging wall largely behaved in a brittle manner, developing significant amounts of pseudotachylyte veins and breccias in a zone up to a few hundred metres wide. Only the lowermost few tens of metres of the pseudotachylyte breccia in the hanging wall were mylonitically overprinted, with subsequent pseudotachylyte veins cross-cutting the mylonitic foliation. Above this zone the pseudotachylyte veins in the hanging wall remain largely unsheared. This asymmetry might reflect lower ambient temperatures in the hanging wall (Camacho and McDougall, 2000) or result from a higher abundance of hydrous minerals in the footwall (Camacho et al., 1995).

Low-strain domains in the footwall reveal that localized shearing initiated along pseudotachylyte veins and that shear zones were in turn exploited by pseudotachylyte formation, establishing a cyclic interplay between fracture and flow in time and space (Figure 1). Neither phyllonitization nor synkinematic growth of new muscovite is observed on a regional scale. In contrast to models with a simple brittle-to-viscous transition, these observations show that continuous cycles of brittle fracturing (pseudotachylyte formation) and shearing (mylonitization) are active in “dry” mid-crustal environments. The product of multiple seismic slip events and ductile shear, repeatedly exploiting the same structural discontinuities, is the formation of composite layers of mylonite/ultramylonite and sheared pseudotachylyte, as frequently observed in the Woodroffe Thrust. In both the footwall and hanging wall, viscous shearing not only localizes on pseudotachylytes, but can also be concentrated along the (chilled) margins of fine-grained dolerite dykes, indicating a possible grain size dependence on the process of strain localization under dry mid-crustal conditions. However, most shear localization occurs on precursor fractures and associated pseudotachylyte and largely ignores any pre-existing compositional layering.

Figure 1. Sample from the Woodroffe Thrust revealing a detailed cyclicity between brittle fracturing (pseudotachylyte formation) and shearing. Three different generations of pseudotachylytes (I, II, III; in order: older to youngest) are observed cross-cutting each other. The two older generations (I, II) are both sheared and each incorporated as sheared fragments within the next younger pseudotachylyte. These observations are consistent with three phases of brittle fracturing separated by two intermediate episodes of shearing.
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