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Swiss Tectonics Studies Group of the Swiss Geological Society

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1.1

Spontaneous initiation of subduction at passive margins – 3D modelling

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The initiation of subduction is a poorly understood process, though subduction is the key process for plate tectonics on Earth. Oceanic lithosphere becomes denser than the underlying asthenosphere within 10 - 50 Ma after it forms at a mid-ocean ridge due to the cooling from the surface. However, despite the favorable gravitational instability and ridge-push, the bending and shear resistance of the lithosphere prevent subduction from arising spontaneously. Subduction initiation at passive margins has been recently investigated numerically in 2D (Nikolaeva et al., 2010), with (i) positive buoyancy and (ii) thinning (e.g. rifting) of the continental lithosphere being the main factors controlling this process. Nevertheless three-dimensional (3D) geometry and dynamics of this process as well as influences from curvature of a passive margin remain enigmatic.

We carried out 3D numerical experiments using the code I3ELVIS to model the spontaneous onset of retreating subduction at a passive margin. We varied model parameters as the thickness of the continental lithosphere, the curvature of the passive margin and the rheological properties of the mantle and the crust.

Similarly to 2D cases (Nikolaeva et al., 2010) three main regimes of passive margin evolution are identified: stable margin, overthrusting and proper subduction. Our models demonstrate that subduction initiation is strongly affected by fluid release from the oceanic lithosphere that begins to subduct. This process is associated with an intense development of partially molten hydrated thermal chemical plumes under the extending continental plate which should result in the strong magmatic pulse related to the beginning of subduction. Our results also suggest that 3D effects arising from margin curvature can be very important for slab geometry and dynamics of subduction initiation.

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1.2

Late Eocene-Oligocene tectonic events in the Anarak area, Central Iran

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The Anarak-Jandaq Terrane comprises a Variscan-Eocimmerian metamorphic basement and a Cretaceous-Cenozoic sedimentary cover exposed along the Paleo-Tethys suture in the NW margin of the Central-East Iranian micro-continent (Bagheri & Stampfl 2008) (figure 1). Although tectono-stratigraphy of the Anarak area is thought to record pre-Triassic subduction processes along the Paleo-Tethys Ocean, closure of this ocean in the Triassic, and Neo-Tethyan back-arc rifting in the Late Cretaceous (Bagheri & Stampfl 2008), our knowledge of the tectonic development of the area is still limited. We have studied structural patterns based on field observations and satellite images. Our results provide a new insight into tectonic development of the Central-East Iranian micro-continent during the Cenozoic and show the Anarak area has experienced at least two deformation events between the Late Eocene-Oligocene and Miocene-Pliocene.

Lithostratigraphic units recognized on geological maps and satellite images in the studied area allow to identify a “mushroom-shaped” structural pattern similar to Type 2 fold interference of Thiessen and Means (1980) (figure 1). This pattern has a symmetry plane oriented NW-SE on a map view. A Miocene-Pliocene deformation phase is characterized by NW-trending open folds observed at some kilometers-scale. Restoration of these folds allowed to recognize an older, Late Eocene-Oligocene deformation phase outlined by SE-vergent, NE-trending closed folds and associated far-displaced nappe thrusts. Newly-recognized deformation events could be related to Neo-Tethyan back-arc closure at the present position of the NE-striking Doruneh Fault and its Late Cretaceous mélange (figure 1). Our results suggest the most prominent struc-
tural patterns of the Anarak area essentially reflect the youngest events of a long tectonic history that remains to be characterized in detail.

**Figure 1**

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1.3

Physical controls of intra-oceanic arc extension and trench migration: numerical modelling

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Modern intra-oceanic subduction zones often develop series of magmatic chains and basins (Stern et al., 2002), (Takahashi, 2008/09), (Larter 2003) and it is not yet fully understood how and why these structures develop. We performed systematic numerical experiments with a 2D coupled petrological-thermo-mechanical numerical model of an intra-oceanic subduction process. Our model includes different slab push velocities, different weakening effects (dehydration of the subducted crust, aqueous fluid transport, partial melting of both crustal and mantle rocks and melt extraction processes), different ages of the subduction slab and the overriding plate as well as spontaneous slab bending. With a long-term model of subduction dynamics, we tested the effects of geometry, rheology, composition, dehydration and melting processes and their influences to the development of extension or compression in intra-oceanic arcs. Based on numerical results we established three different types of extension regimes: i) extension in the fore-arc, ii) extension within the magmatic arc, and iii) no extension, but compression. In general, in all our experiments, the first spreading episode mostly occurs in the fore-arc. Such fore-arc spreading can be observed in the very eastern part of the Aleutian arc system, where decompression melt pierces the thin crust and/or pushes the magmatic arc away from the trench and it becomes a paleoarc, similar to the Kyushu-Palau Ridge (Stern et al., 2003). At the same time a new magmatic arc grows between the trench and the spreading centre. Some experiments show an intra-arc-spreading, such as the active Mariana arc and the inactive West Mariana Ridge (split an initially homogeneous arc into two distinct parts), (Stern et al., 2003). We also found four different trench migration patterns depending on the degree of coupling between the plates: i) trench retreating, ii) episodic retreating and advancing with a total retreat of the trench, iii) trench advancing, iv) stable trench position over time. Our numerical results on episodic trench movements match well with natural observations (Clark et al., 2008) concerning the periodicity in the back-arc tectonic regimes.

1.4

Geodynamics of the Alpine Tethys as traced by detrital zircons (in-situ U/Pb dating and high resolution provenance analysis) - a project layout

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The Triassic-Tertiary Alpine orogenic cycle is recorded in a variety of sandstone-bearing formations. The detrital composition of the sandstone deposits: (i) preserves the record of the source rocks, exposed on the Earth’s surface at particular geological times, and (ii) allows to corroborate large scale tectonic movements which trigger processes like uplift, exhumation and erosion.

In the Alpine range, these deposits include the initial rift and the subsequent continental drift related sediments, then, they are followed by sedimentary units related to continental convergence with lithosphere subduction and as well with the final continent-continent collision stage.

Although in the past, facies and standard provenance analyses (heavy minerals and modal composition of sandstones) have allowed to propose quite comprehensive tectono-sedimentary models, several paleogeographic and tectonics problems still are ambiguous because the complexity of the nappe-tectonics has veiled the original source - basin relationships. Furthermore, the standard provenance analyses have reached their limits of resolution and hardly can provide more details in order to refine paleogeographic models of the Alpine Tethys.

The present research project started at the beginning of year 2010. It is aimed at re-evaluating the geodynamics of the Alpine Tethys by the systematic analysis of detrital zircons in various extension and compression related sandstone units in the Central and Eastern Alps. A widespread sandstone sampling across various paleogeographic domains has been done.
New concepts and analytical methods are applied in this research to complete the standard provenance analyses:

1. U/Pb laser ablation ICP-MS dating of detrital zircons (e.g. Martin-Gombojav and Winkler 2008). This method provides the magmatic and metamorphic crystallization age of the detrital zircons. Concordia diagrams are used to eliminate the odd age points, age range histograms and probability density curves define statistically valid age populations.

2. Trace element contents of the dated zircon (essentially using P, Y, Th, U, Nb, Ta, REE and Hf concentrations) are analyzed in order to determine the igneous rock type, in which grains had crystallized, following the Belousova et al. (2002) method.

3. Hafnium 176Hf/177Hf isotope analysis (e.g. Hawkesworth and Kemp 2006). These isotopes can be related to the crustal residence age (model age) or to the average time elapsed since the source of the magmas, from which the zircons crystallized, were extracted from a mantle reservoir. The 176Hf/177Hf ratio fingerprint the nature of the magmatic source rocks with respect to their derivation from depleted mantle (which indicates that the zircon were formed during the process of new crust formation) or recycled continental crust. Conveniently, as the different measurements can be performed on the same grain, the straight correlation of geological age and geochemical signatures is provided.

The first results from sandstone formations of different paleogeographic origin in the Alpine Tethys show promising results. Mesozoic and Cenozoic deposits of the Central Alps show a wide detrital zircon age range including also reworked Proterozoic grains. A prominent Late Devonian - Permian (350 - 270 Ma) age population is common in various sandstones, which correlates with the Variscan orogeny and post-Variscan extension.

Figure 1. Major paleogeographic units in the Alps showing the location of collected samples for this research.
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1.5
Orogenic development of the Northeastern Andes (Colombia) as revealed by detrital zircons - preliminary results

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The Meso-Cenozoic orogenic history of the Northern Andes is mirrored by a variety of sedimentary deposits, and especially sandstone-bearing formations are of special interest. In the Northeastern Andean range, these deposits include the synrift and the subsequent post-rift sequences and the deposits related to the retro-arc foreland basin formation. The detrital composition of the sandstone deposits reveals the source rocks, which were exposed on the Earth’s surface at particular geological times. Therefore, the study allows corroborating large-scale tectonic movements, which trigger processes like uplift, exhumation and erosion.

The detailed timing for the initial uplift of the Eastern Cordillera of the Colombian Andes is poorly constrained; estimates range from ca. 60 to 5 Ma. The present research is aimed at evaluating the development of the Eastern Cordillera by the systematic analysis of the detrital composition of the different sandstone deposits (heavy minerals and modal composition), and by U-Pb laser ablation ICP-MS dating of included detrital zircons. The detrital composition analysis reveals the position of the basins within a plate tectonic framework and the U-Pb zircon dating reveals the magmatic and metamorphic crystallization age of the detrital zircons. Concordia diagrams are used to eliminate the odd age points; age range histograms and probability density curves define statistically valid age populations.

The detrital zircon U-Pb ages extracted from the intermontane basin (Sabana de Bogotá) along the axis of the Eastern Cordillera (Fig. 1) reveal a change of age-spectra at the Paleogene-Neogene transition by the new occurrence of Late Cretaceous to Tertiary magmatic/volcanic zircons (ca. 90 - 30 Ma). The observed change in the age populations in the intermontane basin corresponds to a change in the provenance regime from the Amazon Craton to Andean rock sources, which can be attributed to differential uplift and erosion of parts of the Eastern Cordillera. However, this shift is not noted in the Llanos foothill deposits (retro-arc foreland basin) to the east where the supply from Amazon Craton rocks continued to dominate (as also supposed by paleocurrent data, Parra et al. 2010). This suggests that a natural tectonic barrier isolated the Llanos basin from Andean input. However, minor input may also have been provided from uplifted Amazon basement in the Andean range as observed in the Oriente basin fill of Ecuador (Martin-Gombojav and Winkler 2008). Similarly, the important detrital change in the intermontane basin of the Sabana de Bogotá approx. correlates with major restructuring of the detrital source terranes during Late Eocene - Oligocene in the Andean transect of the Ecuadorian Andes (Martin-Gombojav and Winkler 2008).

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Figure 1: Simplified geological map and cross sections in the Eastern Cordillera of the Colombian Andes. Black squares represent the studied areas.
1.6

High temperature compaction of hot-pressed Rochester shale powder

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Samples derived from hot-pressed mineral powders are commonly used in experimental rock deformation studies. These synthetic rocks are typically more porous than their natural equivalents. Consequently, deformation is potentially accommodated by pore collapse and bulk compaction, rather than plastic flow. We performed uniaxial compression tests on porous (12.5 ± 1.2 %) hot-pressed natural shale powder to investigate the role of pore collapse and compaction in low strain deformation of phyllosilicate rich material.

Experiments were performed with a gas-medium testing machine under constant temperature (500, 650 and 700 °C), confining pressure (300 MPa) and strain rate ($10^{-6} – 10^{-3}$ s$^{-1}$) conditions. Due to load cell limits and the hardness of the samples, maximum axial strain reachable in these tests was 13%. Hot-pressed (24 h at 590 °C and 160 MPa) Rochester shale powder from New York State – USA (d < 125 µm) was used as sample material. These samples contain 60-70 vol.% illite/mica (d < 5 µm) and 20-30 vol.% quartz (20 < d < 125 µm). Additional minor phases include biotite, K-feldspar, apatite, rutile and pyrite.

Experiments showed two distinct compaction behaviours: 1) Pure shear with pore collapse as primary porosity reducing mechanism and > 45 % compaction recovery. 2) Sample contraction with pore collapse and cementation as porosity reducing mechanisms and < 30 % compaction recovery. Pure shear compaction is characterized by strain rate insensitive work hardening to differential stress levels > 500 MPa at 8 % axial strain. All 500 and 600 °C, and vented sample 700 °C experiments followed pure shear compaction. Work hardening in contractual compaction tests was strain rate sensitive, with reducing hardening rates with decreasing strain rate. Steady state flow could not be established before 13 % axial strain and differential stress still exceeded 300 MPa. Contractual compaction occurred in 700 °C experiments without venting. Compaction behaviour defines the sample strength evolution with strain. Comparison between 700 °C vented and unvented samples under otherwise identical experimental conditions showed that at 10 % axial strain vented samples were 59 % stronger. Similarly, a comparison between unvented compacting samples at 650 and 700 °C displayed a 66 % higher flow stress for the cooler sample. The transition from pure shear to contractual compaction occurs in the temperature range coinciding with that of the dehydration reaction of illite/mica+quartz to K-feldspar+illlimanite+water, according to Perple-X modelling. Additionally, the wet-solidus was modelled at 710 °C for 300 MPa using Rochester shale compositions. Neither melt nor reaction products were observed in SEM imaging.

1.7

Preliminary geodynamic reconstruction of the Late Paleozoic-Jurassic Mongol-Okhotsk Belt in NE Mongolia

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The Mongol-Okhotsk Belt extends from Central Mongolia across eastern Siberia towards the Okhotsk Sea in the northwestern Pacific. The belt was formed in a late stage of Jurassic orogeny in the composite Central Asian Orogenic Belt by the consumption of the Mongol-Okhotsk ocean (MOO) south of the Siberian Craton (Fig. 1). We investigated the Late Paleozoic-Mesozoic sediments associated with the belt in Mongolia in order to evaluate the timing and mode of ocean formation, the subduction and the collision of the framing margins. An advanced provenance analysis is applied, including (1) heavy mineral and sandstone framework grain analysis, and (2) U/Pb LA-ICPMS dating, trace element, and Hf isotope analysis of detrital zircons. The methods are useful for describing the source rock lithologies, and the age and nature of the related plutonic-volcanic input.

Three tectono-stratigraphic units are differentiated in this work: (1) the Adaatsag and Dochgol terranes, which represent the oceanic suture itself, (2) the Hangai-Hentei basin to the northwest of the suture, and (3) the Ereendavaa terrane and
the Middle Gobi volcanic belt to the southeast (Badarch et al. 2002). The latter two are considered as the northern and southern margins of the former MOO (in modern coordinates) respectively. On the northern margin ophiolitic accretionary wedge and fore-arc deposits are recognized. The southern margin is characterised by Devonian-Carboniferous sediments presumably deposited on deformed and metamorphosed Neoproterozoic-Early Paleozoic continental and ophiolitic basement, which initially was accreted against the North Asia Craton (Siberia) by the closure of northern parts of the Paleo-Asian ocean in Ordovician-Silurian (Windley et al. 2007). According to tectono-stratigraphic arguments combined with biostratigraphic and radiometric age data, the MOO is considered to open from Silurian on (Kurihara et al. 2008). Back-arc spreading within the Early Paleozoic collage due to northward subduction of the southern Paleo-Asian ocean under the accreted Mongolian margin was the possible mechanism for the MOO opening.

The Devonian and Permo-Carboniferous syn-sedimentary U/Pb detrital zircon age patterns and Hf isotopic values show similar subduction related magma production processes in the northern and southern margin. However, the two continental margins of the MOO were presumably active at different periods (i.d. later in the southern margin).

Figure 1. Approximate location and extension of the Mongol-Okhotzk Belt with its suture zone (MOO) in the Central Asian Orogenic Belt (from Li 2008).

Our results indicate that along the northern margin, from Silurian to Early Carboniferous, subduction and accretion prevailed, and was re-initiated during the Permian. Few reworked zircon grains were found in the northern margin, whereas in the contemporaneous southern margin many reworked zircon grains coming from Neoproterozoic-Early Paleozoic basement are recognized. The Silurian-Devonian southern margin depicts an extensional continental margin context that turned into an active continental margin with starting arc magmatism in the Carboniferous. Continued subduction is underlined by the occurrence of Permian and Triassic zircons. In both margins, Triassic and Jurassic continental sediments unconformably overlie tectonically deformed fore-arc series.

In the suture zone in-between, Permo-Triassic and Jurassic samples contain Permian zircon grains, and an irregular mixing with Cambrian to Carboniferous zircons is documented. The pre-Permian zircon age spectra are similar with the southern margin age patterns. Syn-sedimentary magmatic activity is recorded until Late Triassic - Early Liassic, which approximately correlates with the time of closure of the MOO in the Mongolian segment of the mountain belt.

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Neogene oblique normal faults and veins in the Rawil Depression (SW Switzerland)

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In the Rawil Depression between the Aar and Mont Blanc massifs, oblique normal faults are very common but, according to published maps and profiles, these faults tend to lose displacement over short distances and do not cross-cut nappe contacts or more incompetent units (e.g. shales and marls). This field study aims to establish:

(1) the orientation and distribution of these faults
(2) the fault geometries and kinematics
(3) the relationship between veining and faulting.

After two field seasons of detailed mapping and fault and vein analysis in the Rawil Depression, we distinguish three post-nappe sets of veins and faults on the basis of their strike orientation: (1) NNW/NW-striking; (2) WNW/W-striking; (3) ENE-striking. Fault set (3) occurs mainly in the Rhône valley, where the fault planes are steep and with a dominant dextral strike-slip component. This set is associated with the Simplon-Rhône Fault, with activity probably throughout much of the Neogene and possibly also into the Quaternary.

Fault sets (1) and (2) generally dip at a low to moderate angle to the SW and typically develop domino-like structures. The major faults in the Rawil area are spaced around 1 km and show similar features, whereas small-scale faulting is much more diffuse. Fault sets (1) and (2) are broadly coeval, as indicated in the Rawil-Plaine Morte area by many examples of branching and bending of one set into the other and by similar displacement directions and deformation fabrics. Nevertheless, there are clear examples (e.g. along the Wildstrubelhütte segment of the Rawil Fault) of set (2) cross-cutting set (1), which establishes, at least locally, a chronological succession of faulting events.

Calcite slickenlines and fibres on fault planes (1) and (2) indicate two main slip directions. The older one is WSW-directed and generally plunges around 25° whereas the younger one plunes S, with a steeper, mainly dip-slip movement. This generally transtensional faulting must largely post-date folding, because faults of sets (1) and (2) obliquely cross-cut the fold system and the fold geometry can be matched to either side.

Folding and the initial stage of normal to oblique faulting developed under very low grade metamorphic conditions, with exhumation during the Neogene related to WSW-extension that was parallel or slightly oblique to the main Alpine fold axis-trend. Locally there is a transition from an initial more ductile mylonitic fabric to cataclasite. Since faults of sets (1) and (2) developed across the ductile-brittle transition in limestones, shales and marls, they may represent fossil seismogenic zones in rocks with high pore-fluid pressure, corresponding to the current depth of active seismic activity at around 8-12 km in the Sion-Sierre region of the Rhône valley.

Veins are very common in the Rawil area and developed throughout the deformation history, ranging from pre- to syn-folding to coeval with later transtensive faulting. A progressive increase in the number and size of veins is observed in the more competent lithologies approaching the main damage zone of oblique faults [sets (1) and (2)], implying increased fluid circulation toward the fault zones. Pressure-solution, often concentrated on stylolites, is also active until very late stages of faulting and veining. Veins in the damage zones in limestones are sheared into the initial mylonitic zones and form a major component, together with the mylonites, in the subsequently developed cataclasites. This progressive embrittlement during faulting may be due to exhumation and cooling during faulting, higher strain rates, or increased pore-fluid pressures.

Clasts of cataclasites within cataclasites establish that there have been repeated cycles of faulting resulting in cataclasite and sealing. Away from the fault damage zones, crosscutting vein relationships and the bending of vein tails indicate a progressive counter-clockwise relative rotation of the stretching direction, from WSW toward S to SSE, which is consistent with the observed change from oblique slip to subsequent dip-slip on faults of sets (1) and (2). Overall, there is an almost 180°, generally (but not exclusively) counter-clockwise change in the stretching direction, from orogen-perpendicular stretching of reclined fold limbs during NW-directed thrusting, to orogen-parallel stretching during the dominant period of veining and oblique, transtensional faulting, to a late period of limited, more orogen-perpendicular extension.
The Adula nappe is a large tectonic unit of the Central Alps, mainly made of highly metamorphic Paleozoic basement rocks. A Mesozoic (and younger?) cover penetrates deep into it as bands and discontinuous relics of highly metamorphic sediments. We report here the first discovery of fossils in these rocks and other stratigraphic observations at the Plattenberg (pt. 3041, 2 km S of the front of the nappe), taking advantage from the excellent quality of the outcrops.

The stratigraphic succession is the following, from basement upwards:

1. The Garenstock augengneiss forms the top of the basement in this area. It often contains brown carbonate nodules of mm size, particularly frequent in its upper part. It also contains a few amphibolite boudins in the core of which eclogite is locally preserved.

2. The gneiss is overlain with a sharp contact by a thin layer of a white quartzite, similar to the quartzite that commonly forms the base of the Triassic in many parts of the Penninic Alps.

3. This quartzite passes transitionally to a thicker alternation of white and grey-bluish dolomites. They are similar to the Triassic of several Lower Penninic nappes.

4. These dolomites are overlain with a sharp contact by a coarse detrital formation mainly made of dolomitic breccias. The dolomitic pebbles are reworked from the Triassic and they can be so closely packed that the rock looks at first sight like a genuine Triassic dolomite ("reconstituted Triassic"). The matrix is quartzitic to dolarenitic, sometimes containing also mica or calcite. At the base the quartzitic matrix can form a dm-thick layer of pure quartzite (not to be confused with the basal Triassic quartzite). Going upwards the matrix of the breccia becomes dominant and the rock gradually passes to a dolo-quartz-arenite. Near the top it may contain a few cm- to dm-thick layers of pure limestone. All these rocks form a well-characterized lithostratigraphic unit that we call the Plattenberg Formation, or Plattenberg Breccia. Discontinuous intercalations or pockets of a reddish rock rich in iron oxides and white mica occur in and at the base of the breccia. We interpret this rock as a (more or less reworked) siderolitic deposit. It gives evidence of post-Triassic emersion and continental erosion before the deposition of the breccia. Three m above the base of the breccia we found in a fine-grained calco-dolarenitic intercalation numerous plates of crinoids (with well preserved details such as the central canal). They prove that the deposition of the breccia occurred in marine (high-energy) conditions.

5. Plattenberg Breccia is overlain by a formation of metapelites passing gradually upwards to a calc-schist. The metapelites contain abundant garnet and smaller amounts of kyanite, chloritoid and graphite. The amount of calcite increases upwards. At their base these metapelites also contain brownish calcareous nodules. The calc-schist contains scattered pebbles of pure limestone. It forms the core of a syncline and consequently it is the youngest stratigraphic unit in this area. Cornieule (rauhwacke) is present. It is deformed and can occupy various positions in the stratigraphic column. It forms a conspicuous m-thick “layer” all along the contact of the metapelites upon the breccia in both limbs of the syncline.

Conclusions:

A. The Adula nappe has its proper sedimentary cover (autochthonous with respect to the basement), comprised of several well-characterized stratigraphic formations.

B. Its Triassic has no affinity with the Briançonnais Triassic. This is important for nappe tectonics, with respect to the recent discovery of a Briançonnais Triassic element below the front of the Adula (in the Luzzone nappe, see Galster et al., this session). Consequently the Luzzone nappe must have had an ultra-Adula origin: it comes from S of the Adula and passed over it before being eventually overtaken by its front.

C. The Plattenberg Breccia is erosive and transgressive. Its basal contact upon the Triassic must represent a large stratigraphic gap, underlined by reworked continental deposits. Comparisons with similar situations in other parts of the Alps suggest a late Early to Middle Jurassic age in a context of extensional tectonics related to the opening of the Alpine Tethys.

D. The occurrence of relatively well preserved fossils (crinoids) in such highly metamorphic rocks is remarkable.

E. The interpretation of the upper metapelite-calc-schist unit is more uncertain, because of the intercalation of a continuous level of cornieule along its base. A large gap is possible, and even a tectonic contact can not be excluded.

F. These results open the door to a geological study of the Adula (and similar highly metamorphic nappes) based on detailed stratigraphic analysis.
One-sided subduction in self-consistent models of global mantle convection: the importance of a free surface and a weak crustal layer

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Previous dynamical models of global mantle convection indicated that a visco-plastic rheology is successful in generating plate tectonics-like behaviour self-consistently (Moresi et al., 1998; van Heck and Tackley, 2008). Yet, these models fail to create Earth-like plate tectonics: so far in all published models subduction is two-sided and more or less symmetric, whereas terrestrial subduction is one-sided and characterized by a distinctive asymmetry.

Figure 1. Viscosity fields for convection with a strongly temperature- and pressure dependent visco-plastic rheology and (top) a free-slip surface or (bottom) a free surface.

One simplification used in previous models is that of a free-slip upper boundary, in which the shear stress is zero but the vertical position of the boundary is fixed. In contrast, subduction zones display some of the largest variations in surface topography on Earth. For the case of a slab that is initially placed at the surface and allowed to freely subduct, Schmeling et al. (2008) showed that it is necessary to include a proper free surface in numerical models in order to reproduce laboratory results. According to their benchmark study, mimicking a free surface by a low viscosity, zero density layer on top of the crust is an adequate approach. For this reason, we have implemented such a “sticky air layer” in our global numerical model.

We here study the effect of a free surface on the mode of subduction in 2-D and 3-D global, fully dynamic mantle convection models with self-consistent plate tectonics. For this we use the finite volume multigrid code StagYY (Tackley, 2008) with strongly temperature- and pressure dependent viscosity, ductile and/or brittle plastic yielding, and non-diffusive tracers tracking compositional variations (the ‘air’ layer in this case).

We observe that indeed, a free surface leads to single-sided subduction, whereas identical models with a free slip upper boundary develop double-sided subduction (Figure 1). A free surface is thus an essential ingredient to obtain realistic subduction behaviour in numerical models, probably because it allows the slab to bend in a natural manner.

Although previous models appear one-sided from the temperature or viscosity fields, there is strong mechanical coupling between the slab and the mantle wedge that makes them mechanically double-sided. Regional models of subduction (Gerya et al, 2008) indicate that one requirement for stable one-sided subduction is a low strength interface between the plates achieved by the presence of metamorphic fluids in the subduction channel. Such a lubrication layer consisting of
weak hydrated sediments is implemented in the above model. It accommodates stable one-sided subduction by strain localization, while the absence of a weak shear zone leads to repeating occurrence of mechanically two-sided subduction since in this case the plastic strength of the entire plates needs to be sufficiently low to allow for subduction.

In conclusion, a free surface is the key ingredient to obtain thermally one-sided subduction, while additionally including a weak crust is essential to obtain subduction that is both mechanically and thermally one-sided.

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1.11
Lower crust extrusion triggered by indentation: Insight from analogue and numerical modelling
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Recent petrological, structural and geochronological studies of the eastern margin of the Bohemian Massif (Czech Republic) suggest a conceptual geodynamical model to explain exhumation of lower-crustal (20 kbar, 800 °C) felsic rocks. The model involves indentation of a weak orogenic lower crust by an adjacent rigid mantle lithosphere, resulting in crustal scale buckling of the weak orogenic lower/middle crust interface followed by extrusion of a ductile nappe over the rigid promontory.

The hypothesis has been checked using both analogue and numerical models. Analogue experiments using a three layer sand-silicone setup were carried out in Rennes laboratory (France). Results show that the most important features of the conceptual model can be reproduced: extrusion of lowermost silicone over the indenter and flow of horizontal viscous channel underneath a rigid lid above the actively progressing promontory. Furthermore, experimental results show that a plateau develops above the channeling lower crust.

Two sets of sandbox scale numerical simulations were performed. The first set of experiments is designed to study the influence of viscosity stratification within the crust on the extrusion process. A second set of experiments were performed in order to quantify the influence of the viscosity and the geometry of the indenter. Non-dimensional scaling laws were derived to predict the maximum extrusion rates associated with the indentation mechanism. Such laws enable to compute vertical extrusion rates that are in good agreement with natural exhumation rates.
1.12

2D Numerical modelling of a porous flow in a deforming viscoplastic matrix with finite differences and marker-in-cell techniques

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Numerical modelling of a porous flow has a wide range of applications in geosciences and industrial engineering. For example, numerical modelling of subduction-related magmatic arcs includes the process of generated magma migration to the region above the subducting slab through the porous medium. This kind of fluid transport is a coupled chemical, thermal and mechanical process.

We created a two-dimensional model of a two-phase flow in a porous media solving a coupled Darcy-Stokes system of equations for two incompressible media for the case of visco-plastic rheology of solid matrix. We use a finite-difference method with fully staggered grid in a combination with marker-in-cell technique for advection of fluid and solid phase. We performed a comparison with a simple benchmark of a thermal convection in a closed bottom-heated box to verify the interdependency of Rayleigh and Nusselt numbers with theoretical ones.

In the future we plan to include elasticity of a solid phase, fluid/solid compressibility and melting in our numerical model as a function of pressure, temperature, water content and composition.

Ultimate goal is to simulate in a realistic self-consistent manner fluid and melt generation and transport in subduction zones including fluid/melt focussing phenomena.

1.13

Neogene tectonics of the Mont Blanc area

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The Mont Blanc massif forms part of the chain of External Crystalline Massifs, has the highest topography in Europe (up to 4'810 m) and has had a young exhumation history, with apatite fission-track ages ranging down to 1.4 Ma (Seward & Mancktelow 1994). There is now a quite extensive low-temperature thermochronology data set that can be used to estimate exhumation rates in the Mont Blanc region during Neogene times (e.g. Seward & Mancktelow 1994; Leloup et al. 2005; Glotzbach et al. 2008). Glotzbach et al. (2008) propose an episodic exhumation with rates changing from relatively fast (~2.5 km/Ma before 6 Ma) to a slow phase (~0.5 km/ Ma between 6 and 3.5 Ma), in turn followed by acceleration to ~1 km/Ma after 3 Ma. Various models have been proposed to explain this young exhumation but detailed structural studies to critically assess and constrain the proposed kinematic models are largely lacking.

The tectonic framework of the Mont Blanc area is dominated by three major structures. On the western side, the massif is bordered by the Chamonix zone, which is dominated by north-westward thrusting of the Mont Blanc massif over its sedimentary cover. Leloup et al. (2005) dated this thrusting to be active around 16 Ma. Dextral movements along the Chamonix zone were described by Gourlay & Ricou (1983) and this zone has been proposed to be the direct southward continuation of the dextral transpressive Rhône-Simplon fault zone.

On the eastern side of the massif, the most prominent structure is the Frontal Pennine Thrust, which several authors have suggested might have been reactivated with a normal movement sense in the Late Neogene, contributing to exhumation of the Mont Blanc massif (e.g. Seward & Mancktelow 1994).

The third important structure is a major back-thrust proposed by previous authors ("Mont Blanc back-thrust", e.g. Leloup et al. 2005, Rolland et al. 2007). This has been described as a relatively steeply north-west dipping thrust bringing the Mont Blanc basement back over the tectono-stratigraphically higher Helvetic and Ultrahelvetic metasediments. The current
study presents new structural data from all around the Mont Blanc massif and the adjacent sediments. It focuses on the three main tectonic structures and addresses the tectonic evolution and late stage exhumation history of the massif. We can show that normal reactivation of the Pennine Frontal Thrust is either very small or non-existent and we therefore consider that reactivation along this fault does not play an important role in the exhumation of the Mont Blanc massif. Leloup et al. (2005) describe the Mont Blanc back-thrust as being reactivated at around 2.5 Ma and to be responsible for the latest pulse of exhumation of the Mont Blanc massif. However, this back-thrust is actually slightly folded, with a younger weak axial plane cleavage cross-cutting the thrust, and therefore is unlikely to be responsible for the very young exhumation of the Mont Blanc massif.

Strike-slip movements with nearly horizontal lineations, slickenfibres, or striae can be observed throughout the whole field area. For both ductile and brittle structures, the main direction is oriented NE-SW with a right-lateral sense of shear. Paleo-stress reconstructions from the eastern side of the massif indicate a local NE-SW compression. For such a compression direction, the Mont Blanc massif would lie in the position of a restraining bend within the Rhône-Simplon fault system, possibly resulting in a positive flower structure that would exhume the massif. However, since no young structures directly related to exhumation have been found, we expect this situation to have been active earlier in the exhumation history (Miocene?) and not to be related to the final uplift. We therefore suggest that the most recent uplift of the Mont Blanc relative to its surroundings is more widely distributed and not restricted to discrete structures bounding the massif itself.

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1.14

The not-so-simple effects of boundary conditions on models of simple shear

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Analogue modeling of geological structures, such as the behavior of inclusions in a matrix or folding instabilities commonly employs a linear simple shear or general shear rig. In theory, a homogeneous plane strain flow is prescribed at the boundaries of such deformation rigs, but, in practice, the resulting internal deformation of the analogue material (commonly paraffin wax or silicone putties) often strongly deviates from the intended homogeneous strain field. This can easily lead to misinterpretation of such analogue experiments.

We present a numerical finite element approach to quantify the influence of imperfect simple shear boundary conditions on the internal deformation of a homogeneous viscous analogue material. The results (Figure 1) demonstrate that imperfect circumferential boundary conditions in the simple shear plane (x-y-plane) lead to the heterogeneous strain observed in some analogue experiments (Price and Torok, 1989; Sengupta and Koyi, 2001), depending on their design.
However, in other experiments, the analogue material lies on top of a weak lubricating material (e.g. Vaseline) or is sandwiched between two such materials (Ildefonse and Mancktelow, 1993; Grujic and Mancktelow, 1995). These layers lead to a viscous drag force acting on the surface of the analogue material that represents imperfect simple shear boundary conditions in the third dimension (z-direction). For this experimental configuration, the numerical results (Figure 2) show that the lubricating layers are responsible for the heterogeneous strain observed in analogue models.

The resulting errors in internal strain can be as high as 100% and these important boundary effects, which are difficult to avoid, must be considered when interpreting analogue simple shear experiments.

Figure 1. Numerically deformed homogeneous square with an applied simple shear strain $g_{ext}=0.5$. The for boundary conditions for perfect simple shear are given in the table. In a), only three and in b) to d), only two of them are applied. The applied boundary conditions are noted at each boundary. Thick black lines are passive marker lines. The color represents the second invariant of finite strain, plotted as the error in percent relative to perfect simple shear. Thin black lines are the ±10% contour lines. The area with an absolute error smaller than 10% is given in the lower right corner of each subfigure. Arrows represent the finite perturbation strain.

Figure 2. Numerically deformed homogeneous square with increasing applied simple shear strain $g_{ext}$, perfect simple shear boundary conditions in the x-y-plane and viscous drag-boundary conditions in the third (z-) direction. The color represents the finite shear strain (lower inset figures) and the finite rotation angle (upper inset figures), respectively, both plotted as the error in percent relative to perfect simple shear. Thin and thick black lines and arrows are the same as in Figure 1. The bold blue and red line represent the finite shear strain and the finite rotation angle at the very center of the model, respectively.
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1.15
The Soja and Luzzone nappes: discovery of a Briançonnais element below the front of the Adula (NE Ticino, Central Alps)

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The Soja nappe is a small tectonic unit situated below the front of the Adula nappe in NE Ticino. It is classically characterized by a dam- to hm-thick sliver of paragneiss of presumed Late Paleozoic age, partly conglomeratic (sometimes called “Verrucano”), and is traditionally considered as rooted below the Adula nappe. Stratigraphic and structural analysis based on detailed mapping of this gneissic body and its Mesozoic cover reveals the following facts:

1. The classical Soja nappe consists of two distinct parts separated by a wide landslide:
   a. A southern part extends over 3.5 km NW of Val Soi (the type-locality) before it disappears below the landslide.
   b. NE of the landslide, the gneiss can be followed over 7.5 km in the slopes S of the Lago di Luzzone and in the Valle di Garzora.

Each part is homogeneous in its stratigraphic content, while there are significant differences between the southern and the northern parts, as explained below. Consequently their connection below the landslide is improbable and we better consider them as two distinct tectonic elements. The southern element is by definition the Soja nappe s.str. We call the northern element the Luzzone nappe.

Both nappes have the structure of an isoclinal anticline with a Paleozoic core. Mesozoic is well developed in both limbs of the Luzzone nappe, but only in the normal limb of the Soja s.str. nappe.

2. Old gneiss: The Soja s.str. element contains an anticlinal core of gneiss with hints of pre-Alpine metamorphism. The Luzzone nappe shows no evidence of such an old, polymetamorphic gneissic basement.

3. Late Paleozoic paragneiss: This is the characteristic lithology of the classical Soja nappe.
   a. Luzzone nappe: It mainly consists in well-bedded, fine-grained, micaceous and chlorite arkosic meta-sandstones. Dark brown spots of an ankeritic carbonate are omnipresent. In its upper part it may contain thin layers of dolomite and conglomeratic intercalations. This formation shows definite affinities with the Moosalp Formation in central Valais, of Permian age, which is a characteristic lithostatigraphic unit of the external part of the Paleozoic Briançonnais paleogeographic domain, or, in tectonic terms, of the lowest tectonic elements of the Grand St-Bernard nappe S of Visp (Zone Houillère and the overlying St-Niklaus syncline).
   b. Soja nappe s.str.: The general lithology is similar but the carbonate spots or intercalations are rarer. In the inverse limb of the nappe the stratigraphically upper part is enriched in conglomerates. The Moosalp-type characteristics are less obvious.

4. Triassic: In both nappes the paragneiss is overlain by a white, pure quartzite (presumed of Early Triassic age) that passes transitionally to a thick series of limestones and dolomites. This carbonate series differs in the N and S elements:
   a. Luzzone nappe: The carbonate series displays typical characteristics of the Triassic Briançonnais domain. Even if tectonic deformation prevents to draw a complete stratigraphic column, very characteristic facies can be identified. Most typical is the St-Triphon Formation (of Anisian age), characterized by its calcaires vermiculés with their specific ichnofossils. The stratigraphic transition from the quartzite to the carbonate sequence, well exposed at several places with alternating layers of quartzites, greenish metapelites and dolomites underlying a first m-thick bed of yellow dolomite, can also be convincingly parallelised with the base (Dorchaux Member) of the St-Triphon Limestone in classical Briançonnais cross-sections. The Carnian dolomitic breccia has also been recognized. These
features definitely assign the Luzzone Triassic to the Triassic Briançonnais domain.

b. Soja nappe s.str.: The dolomites predominate, but thin layers of limestone are also present at the base. Several distinct levels of dolomite have been identified and present a good lateral continuity. No typical Briançonnais feature has been observed.

5. Jurassic: Absent in Soja s.str. It is well developed in both limbs of the Luzzone nappe as a dam- to hm-thick series of dark blue or black pelitic schists and calc-schists, classically presumed Liassic (to early Dogger?), an age that we consider as very probable. Our observations confirm that the contact of this series upon the Luzzone Triassic is stratigraphic. This series is overthrust by another one with a very similar lithology, where the presence of a Sinemurian ammonite (Arnioceras sp., A. Uhr, unpubl.) supports the stratigraphic interpretation. Both together belong to the Piz Terri – Lunschania zone of the literature. This means that a large part of the Piz Terri – Lunschania zone belongs to the Luzzone nappe, which extends considerably the surface of this tectonic unit towards NE. Characterized by two relatively coarse detrital inputs above a mainly marly base and topped by a black calcite-free pelite, these series show a clear affinity with the Helvetic (s.l.) Liassic stratigraphy.

Conclusion:
The most important point is the typical Briançonnais affinity of the Palaeozoic and Triassic sections of the Luzzone nappe. Particularly in the Triassic, the observed features belong to the core of the definition of the Briançonnais domain s.l. (i.e. including the Subbriançonnais) and of its use as a tool for paleogeographic correlations along the Alpine arc (Briançon Alps, Vanoise, Préalpes Médianes and Grand St-Bernard nappe in central Valais). As the Adula Triassic is not Briançonnais (see Cavargna-Sari et al., this session), the Luzzone nappe (including a large part of the Piz Terri – Lunschania zone) must have an ultra-Adula homeland. Originating S of the Adula, it must have passed over it, probably during subduction of the Adula, to be finally overtaken by its front when the Adula nappe was exhumed.

Another remarkable point is the Helvetic affinity of the Liassic section of the same Luzzone nappe. The stratigraphic superposition of a Jurassic series of Helvetic (s.l.) type over a typically Briançonnais Triassic has major paleogeographic implications.

The classical Soja nappe is often correlated with the Lebendun nappe of NW Ticino and Italy. Our observations in both areas show that the similarity of the Lebendun gneiss with the Soja or Luzzone gneisses is superficial. The Soja s.str and the Luzzone nappes have nothing to do with the Lebendun.

1.16
Morphologic evolution of the Central Andes of Peru

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We analysed the morphology of the Andes of Peru and its evolution based on the geometry of river channels, their bedrock profiles, stream gradient indices and the relation between thrust faults and morphology.

The rivers of the Pacific basin incised Mesozoic sediments of the Maraçon thrust belt, Cenozoic volcanics and the granitic rocks of the Coastal Batholith. They are mainly bedrock channels with convex upward shapes and show signs of active ongoing incision. The changes in lithology do not correlate with breaks in slope of the channels (or knick points) such that the high gradient indices (K) with values between 2000-3000 and higher than 3000 suggest that incision is controlled by tectonic activity. Our analysis reveals that many of the ranges of the Western Cordillera were uplifted to the actual elevations where peaks reach to 6000 m above sea level by thrusting along steeply dipping faults. We correlate this uplift with the Quechua phase of Neogene age documented for the Subandean zone (see Fig. 1).

The rivers of the Amazon Basin have steep slopes and high gradient indices of 2000-3000 and locally more than 3000 in those segments where the rivers flow over the crystalline basement of the Eastern Cordillera affected by vertical faulting. Gradient indices decrease to 1000-2000 within the east-vergent thrust belt of the Subandean zone. Here a correlation between breaks in river channel slopes and location of thrust faults can be established, suggesting that the young, Quechua phase thrust faults of the Subandean zone, which involve Neogene sediments, influenced the channel geometry. In the eastern lowlands these rivers become meandering and flow parallel to anticlinal structures that formed in the hanging wall of Quechua phase thrust faults, suggesting that the river courses were actively displaced outward into the foreland.
Figure 1. Morphologic expression of Neogene thrusting (Quechua phase) in the Central Highlands (near Abra la Viuda). The schematic cross section shows the geometry of thrusting responsible for the uplift of the Early Cretaceous strata. Incaic phase folding of the Cretaceous strata is pre-Calipuy (pre-Oligocene), while Quechua-phase thrusting is post-Calipuy (post-Oligocene).

1.17

Ti in quartz geothermometry in mylonites of the Simplon fault zone. What can we learn?

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The Simplon Fault zone (SFZ) is a major detachment fault between the Upper and Lower Penninic Units in the Central Alps and comprises mylonitic quartz microstructures deformed under the presence of water (Mancktelow & Pennacchioni 2004 and references therein) at metamorphic conditions ranging from lower greenschist facies (N) to upper amphibolite facies conditions (S). In order to study strain localization history in this large-scale structure, different sample series were collected in profiles across the Simplon fault to investigate the changes in dynamic recrystallization mechanisms and recrystallized grain size of quartz.

In the case of pure quartz mylonites (former qtz veins and qtz lenses), fine-grained recrystallized and large ribbon quartz grains occur within a 500 meter wide high strain zone. The recrystallized grain size in this fault zone generally is reduced compared to the undeformed veins, but the degree of grain size reduction varies strongly. The mechanisms of dynamic recrystallization are not only a function of the distance to the SZ, but also of strain localization, depending on the particular strain rate and temperature conditions (Hirth and Tullis, 1992 and Stipp et al. 2002, 2010). In order to track down the effect of temperature, titanium-in-quartz geothermometry (TitaniQ, Wark & Watson 2006) was applied using LA-ICPMS on thick slices of quartz, displaying both, host grains (also ribbons) as well as dynamically recrystallized grains. In this way, a sample series covering a range of distances to the shear zone from 3 m to 1866 m was investigated. Temperatures were calculated using the equation of Wark & Watson 2006 and Ti activities of 0.6, 0.8 and 1.0:

$$T(°C) = \frac{-3765}{\log(X_{qtz}^{Ti}) - 5.69} - 273$$
In the studied quartz microstructures we obtain a temperature variation from 360 up to 470°C. Interestingly, the samples at the farthest locations to the shear zone center display the highest temperatures, whereas samples near the SZ center yield temperatures of around 360 °C. Despite this general temperature trend, local deviations enable interesting insights into the timing and the processes involved into chemical equilibration of Ti in quartz. For example, in the case of strongly elongated quartz ribbons, which were deformed under low temperature plasticity under absence of dynamic recrystallization, still the 460°C temperature event is preserved. This observation suggests that the quartz grains survived a first stage of large-scale strain localization and was only deformed during a late deformation event during which dynamic recrystallization was disabled in quartz. On the other hand, host quartz grains embedded in a fine-grained recrystallized quartz mylonite display the same low temperatures as found in the surrounding recrystallized aggregates. In this case, we assume a synkinematic formation of the quartz veins under low temperature conditions, where the host quartz was only partly recrystallized. We therefore conclude that most of the host grains show inherited temperatures reflecting either high or low temperature deformation, depending on their age of formation. Only the combination with measurement of the recrystallized matrix allows a further discrimination with this respect. In this sense, TitaniQ can indeed be a powerful geothermometer in quartz mylonites, provided that the measurements are accompanied by careful microstructural analyses and the careful selection of the samples with respect to the kinematic framework of the large-scale shear zone.

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1.18
Northern Alpine foreland deformation in western Switzerland: New insights from field and seismic data of the Plateau Molasse

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In our study we investigate the Late Caenozoic tectonic evolution in the northern foreland of the western central Alps in a field based approach.

The western Swiss Molasse basin rests passively on top of a decollement that developed as the Jura Mountains formed the thin-skinned northern alpine foreland fold and thrust belt. Asymmetric Oligo-Miocene foreland basin sedimentation led to a thickening of the sedimentary pile towards southeast. In the Jura Mountains the distal Molasse deposits became eroded from top of the strongly folded frontal part of the foreland fold and thrust belt. In contrast the thicker sediments of the Plateau Molasse in the internal parts are only very gently folded.

Structural field mapping in the Plateau Molasse of the larger Fribourg area revealed regional extended strike slip tectonics, expressed in NW-SE striking dextral and N-S striking sinstral fault zones. In the sandstones, mudstones and rare conglomerates of the Lower Freshwater and Upper Marine Molasse (USM and OMM) of the Plateau- and Subalpine Molasse we observed the following brittle structures: joints and fractures, slickensides, brittle deformation bands in sandstones and pitted pebbles in conglomerates. The brittle deformation is not uniformly distributed. Areas of undisturbed rock are present, separated by strongly fractured areas with well developed meso-scale faults containing cataclasites and fault gauges. The faults are arranged in en-echelon geometries forming Riedel-shear type fault zones. The established paleo-stress field was found to be homogeneous with σ1 orientated NNW-SSE.

The seismic activity in the region is low to moderate, fitting well the meso-scale soft linked discrete faults mapped in the surface outcrops. The focal mechanisms of instrumentally recorded earthquakes during the last decades reveal predominantly strike slip faulting located in the Mesozoic and Tertiary cover units. The stresses derived from these focal mecha-
nisms indicate a NW-SE compression and hence roughly the same as paleostresses derived from the mapped structures in the Molasse and from large scale fold- and thrust orientations in the Jura Mountains. This suggests that post mid-Miocene deformation is a continuous process until present.

The deep structure of the region is given by recent seismic interpretation and reveals a decoupling into three structural levels, representing the basement and the Mesozoic and Tertiary cover units. While basement and Mesozoic strata are pre-fractured, the Tertiary Molasse was undeformed prior to upper Miocene decollement tectonics. The basement is pre-fractured by Permo-Carboniferous normal faults of ENE-WSW strike. In the Mesozoic strata evidence is given for probably synsedimentary N-S striking normal faults. In response to the NW-SE compression of the Miocene to recent stress field the normal faults in the basement should become reactivated as reverse faults and the ones in the Mesozoic as sinistral strike slip faults. While sinistral strike slip faulting probably translates to the surface, reverse faulting in the basement is only evident from seismicity in the frontal parts of the Jura Mountains. The previously undeformed Molasse develops a conjugate dextral and sinistral fault zones system composed of Riedel-type arranged meso-scale faults. Direct kinematic linkage between the three structural levels is lacking. Instead a clear decoupling between basement and cover by the mechanically weak Triassic evaporites and a change of structural style from reactivation of structures to initial faulting between Mesozoic and Tertiary cover units is evident.

1.19

Dynamic constraints on crustal-scale rheology from the Zagros Mountains

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The Zagros Mountains are a spectacular example of a mountain belt that consists of crustal-scale folds with a regular spacing of ~15 km. Despite excellent geological constraints, the formation of these structures remains enigmatic. Here, we therefore use visco-elasto-plastic numerical models to understand the dynamics of the Zagros on geological time scales. Models with a brittle crust and a single basal salt layer produce fault-related deformation structures that are inconsistent with the data. If, on the other hand, we take into account the observation that there might be up to 3 intermediate weak layers within the brittle crust, our models produce crustal-scale folds with the correct wavelength. Physically, this is caused by a folding instability whose wavelength mainly depends on the friction angle of the crust and the viscosity of the detachment layers. By combining a new semi-analytical technique with independent constraints on the effective viscosity of salt, we show that the friction angle of the crust in Zagros should be smaller than ~10° to reproduce observations. Our results have implications for the deformation of the crust as they highlight the importance of thin detachment layers. Moreover, our results show how geological observations put constraints on the long-term rheology and dynamics of the crust.
1.20
Numerical modeling of two-phase flow: Interaction of magmatism with active tectonics

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We investigate the behaviour of a two-phase system that involves production and percolation of partial melt through a viscoelastoplastic continental lithosphere and crust under ongoing tectonic deformation. Using two-dimensional numerical simulations we examine the coupled magmatic and tectonic processes leading to intrusive rock formation.

The numerical modeling approach is based on the assumption that the melt fraction is equal to the porosity of the rock and that porosity change reflects, apart from melting and crystallization, the compaction or dilation of the matrix framework due to both viscous and elastic processes. Both modes of compaction are connected to the local effective pressure, which is obtained as the difference between the bulk pressure over both phases and the local fluid pressure. The magmatic model is chosen to represent a typical melt evolution starting with an arc-type basaltic melt that will fractionate into mafic cumulates and more highly evolved melt, which will again crystallize as a felsic plutonite rock. Compositional contamination by melting of crustal rocks during the magma’s ascent is taken into account.

The model setup involves a continental crust of 50 km thickness and 100 km of the underlying mantle. At the lithosphere-asthenosphere transition, we introduce a source region for partial melt by applying an initial temperature slightly above a wet mantle solidus. The melt production and propagation depends on the evolution of temperature and dynamic pressure in the lithosphere and crust as the region is being deformed tectonically. Here, we focus on extensional tectonics as they provide the best conditions for the extraction of mantle melt. Compressional and transpressional tectonics will be the subject of further investigations.

First results indicate that melt propagation is strongly related to the regional stress field, and that brittle fault zones form important conduits for the propagation of partial melt, especially through the more competent parts of lithosphere and lower crust. Where the partial melt reaches either mechanical barriers or neutral buoyancy with respect to the host rock, regions of magma accumulation may quickly evolve into magma chambers with melt content exceeding 80%. There, the melt may either reside until it crystallizes or fractionate until the more evolved rest of the melt has obtained new buoyancy to force its way further through the crust.

A possible application of such models is to deepen the understanding of the processes involved in, and the geometry and field relations expected from, the emplacement of hydrated slab melts into the overriding continental plate in an oceancontinent subduction setting.

1.21
Fission-track constraints on the thermotectonic evolution of the Apuseni Mountains (Romania)

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The Apuseni Mountains, located inside of the Carpathian arc and bounding the Transylvanian basin to the west, constitutes the largest outcropping part of the Tisza block. This crustal fragment consists of a stack of several nappe sequences formed in response to continental collision, which followed the closure of the Neotethys Ocean. The northwestern part of the Apuseni Mountains represents a coherent nappe sequence consisting of the Bihor and Codru nappe systems. The tectonically highest Biharia nappe system, previously considered as part of Tisza plate (Csontos and Vörös 2004), is attributed to the Dacia Mega-Unit (Schmid et al., 2008).
The first Alpine tectonic event in the area was probably related to the obduction of the Eastern Vardar Ophiolitic unit (Transylvanides) onto parts of the Dacia Mega-Unit (Biharia) in the latest Jurassic. This was followed by late-early Cretaceous final closure of the Neotethys remnants and the collision between Tisza and Dacia blocks producing top-E nappe stacking. The final emplacement of the nappes in the Apuseni Mountains involving top-W to NW superposition of the Biharia, Codru and Bihor nappe systems have taken place in the Turonian. Subsequent compressional deformations in the area are reported for the end of the Cretaceous and the Eocene.

The Jurassic volcanic of the Transylvanides, their sedimentary cover and the underlying Baia de Aries nappe (the highest structural unit of the Biharia nappe system) exhibit late-early Cretaceous zircon fission-track (FT) ages (Aptian and Albian, 120-103 Ma). The more westerly and structurally lower units (Biharia nappe of the Biharia nappe system, Codru and Bihor nappe systems), however, exhibit Late Cretaceous (Turonian to Campanian, 95-71 Ma) zircon FT ages. The late-early Cretaceous zircon FT ages from the Baia de Aries nappe, together with the Jurassic ophiolites and their sedimentary cover, suggest that these rocks must have been buried to a minimum of 8 km during this time. Such temperatures have probably been attained during underthrusting of these units below the Tisza megatectonic unit (thrusting being top-east).

The ages obtained from the Bihor, Codru and Biharia nappes (Turonian to Campanian, 95-71 Ma) correspond to the age of the late Cretaceous top-NW event that led to the present-day nappe stack in the Apuseni Mountains. The internal parts of the Baia de Aries nappe and the overlying Transylvanides were not reheated during this second event since they occupied the highest tectonic position. Zircon FT ages, combined with thermal modelling of the apatite FT data, show that rapid post-tectonic cooling of the area during the late Cretaceous was followed by relatively slow cooling during the early Paleogene.

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1.22
State of the art of SWAM: Seismic Wave Attenuation Module
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The study of wave attenuation in partially saturated porous rock over a broad frequency range provides valuable information about the fluid system in reservoirs, which is inherently a multiple phase fluid system. Until now, few laboratory data have been collected in the seismically relevant low frequency range. Therefore, actual data on partially saturated rock are very limited. The main goal of our work is to accurately measure the bulk seismic attenuation at site conditions in laboratory. Bench top results show consistency with the few reported experimental data of dry, partially and fully saturated rocks.

We report the new apparatus setup to measure seismic wave attenuation at room pressure and temperature on a rock sample of 60 mm length and 25.4 mm diameter. Our method uses bulk strain measurements, accomplished by measuring the strain across the whole sample with micro-linear variable differential transformers. We can cover the frequency range from 10-1-102 Hz.

The results on a sample of Berea Sandstone, with different degrees of saturation, and the calibration data obtained with a standard aluminium sample are described. The acquisition software and the hardware are presented, together with the final goal: the implementation of the attenuation module within a Paterson gas-medium apparatus. This adaptation will allow conducting experiments at confining pressure and depth-temperatures.
1.23
Tectonic amalgamation and reworking of a sedimentary cover within a polydeformed basement in a subduction-collision zone: an example from the Western Italian Alps

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The Dent Blanche nappe belongs to the Austroalpine domain of the Western Italian Alps and is classically divided into two units, the Valpelline and the Arolla Series. The Valpelline Series consists of metapelites, mafic and carbonate rocks with a dominant metamorphic imprint under amphibolite to granulite facies conditions of pre-Alpine age. The Arolla Series is mainly composed of Permian age granite, diorite and gabbro, all metamorphosed and deformed to orthogneiss, Wm-Am-bearing gneiss and schist during the Alpine tectonometamorphic evolution.

The Roisan Zone is considered to be the Mesozoic metasedimentary cover of the Dent Blanche nappe. It comprises ophiolite-free metasedimentary sequences, including Triassic dolomite, Jurassic and Cretaceous calcschist and Qtz-bearing micaschist. This cover is dismembered into metric to hectometric bands and pods and is frequently associated with the Arolla tectonites and mylonites.

The Dent Blanche nappe records a complex structural evolution in which the kinematics of the deformation vary both spatially and temporally. The present study investigates variations in structural style, intensity and geometry of deformation in the Arolla Series and in the Roisan zone. Our data indicate a complex kinematic history involving both crustal extension and shortening during the Pre-Alpine and Alpine evolution. An Alpine polyphase deformation is well developed both in the basement and cover units. The structural evolution comprises two phases of isoclinal folding associated with the development of a penetrative mylonitic foliation. Progressive tectonic modifications of geometric relationships within the whole lithostratigraphic sequence of the Roisan Zone (tectonic amalgamation with a pre-existing basement, re-foliation, transposition) severely alter the original successions of sedimentary layers and the lithologic relationships with the Arolla intrusive complex.

During Alpine deformation phases the igneous and metamorphic protoliths were mylonitized and largely converted to strongly foliated and linedate tectonites. However, heterogeneous strain distribution at the scale of the Dent Blanche nappe allowed for the preservation, at a range of scales, of pre-Alpine relics of all protoliths.

In the Arolla Series strain gradients and the partitioning of deformation are responsible for the juxtaposition of three fabric styles (coronitic, tectonitic and mylonitic domains), which lead to further differentiation. The Arolla unit displays, as a whole, a widespread Alpine reworking that is most evident in the mostly fine-grained Wm±Gln±Chl-bearing orthogneisses and mylonites. Despite this pervasive Alpine imprint, large scale relic bodies of undeformed Permian protoliths (i.e. granite and quartzdiorite) occur as kilometrical and hectometric pods. These preserved cores (termed coronitic domains) are surrounded by medium- to high-strain domains, characterized by tectonitic to mylonitic Wm±Gln±Chl-bearing gneiss. Metric bands of flaser quartzdiorites to mylonites delimit these undeformed pods within the unit. Transitions from massive metagranitoids to mylonitic types are commonly outlined by coarse augengneisses to very fine-grained derivate. Tectonitic fabrics represent a moderate deformational overprint and permit the inference of a chronological succession of deformational phases, going from coronitic to fully reequilibrated mylonitic domains. In the latter are usually devoid of relics.
1.24

Thrusting and faulting in the Préalpes Médianes

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The study of tectonic and neotectonic structures of the Préalpes Klippen with focus on the investigation of fracture families and their possible attribution to an appropriate tectonic event is the scope of an ongoing PhD research.

The Préalpes klippen are formed by a series of nappes that were detached from their Briançonnais homeland as result of its incorporation into the orogenic wedge. Subsequently, they were transported towards the N-NW and emplaced onto the foreland, where they remain as several tectonic klippen along the northern front of the Swiss and French Alps and in the NW of the Helvetic nappes. The most important and best exposed nappe, the Préalpes Médianes, is subdivided into two parts: the Préalpes Médianes Plastiques (PMP), mainly governed by large-scale fault-related folds, and the Préalpes Médianes Rrigides (PMR), dominated by imbricated thrust slices dipping to the N/NW.

Field investigations mainly in limestone, but also in marls and shales of both parts of the Préalpes Médianes exposed a whole suite of brittle tectonic features: joints and fractures, slickensides, vein arrays and stylolithes as well as strongly deformed brittle shear zones. Field measurements combined with more large-scale structural observations in the field, on maps, digital elevation models or orthophotographs allow us to distinguish several structural elements we would like to present:

• Thrusts developed during the emplacement of the Préalpes Médianes were responsible for the folding of the nappe. For this reason, they are for the most part hidden below anticlines. Their general movement direction is top to the NW, however, as observed in the Schopfenspitz area (PMP), important backthrusts with top to the SE orientation exist. The Schopfenspitz backthrust is characterised by an important fault zone of several meters width with well developed shear bands.

• Several faults are oriented transverse or even perpendicular to the fold-axis and induce therefore a segmentation of the large folds. The succession of several normal faults lead to more pronounced plunging of the fold axis. Slickenside and vein data as well as the morphological observations expose axial parallel extension in the Dent de Broc region (PMP).

• Out-of-sequence thrusts - post-dating the emplacement of the nappes - clearly cross-cutting and off-setting pre-existing folds were found both at the Schopfenspitz and the Gros Haut Crêt area (PMP), where due to lateral ramp thrusting a strike-slip component is added.

• Elsewhere, a strike-slip component prevails over the normal fault movement. Throughout the Préalpes Médianes, fracture analysis shows two major fault orientations: right lateral WNW-ESE and left lateral NNW-SSE striking faults. These two fault families are possibly linked to a common conjugate fault system.

Comparison of fault patterns in the Molasse Basin and Préalpes Médianes show striking similarities in fault and stress orientation but the connection of these is still part of discussions.
1.25
An optimal, scalable finite element based forward model for gravity computations

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The use of forward models to compute synthetic gravity signals is necessary to conduct an inversion of the density structure in the subsurface. Numerous forward models exist, the most common of which is a direct summation approach employing an analytic expression to compute the gravity over a rectangular prism. To permit the description of a detailed density structure, the domain is discretised into a set of prisms, each of which possess a unique density. The gravity at a single point s, is computed by evaluating the closed form expression for the gravity over each element, and summing the result.

The summation approach has several disadvantages. The operator F (i.e. the matrix) describing the forward model is completely dense. For inversions, the operator $F^T F$ or $F F^T$ is often required, and both these products will be dense if $F$ is dense. Consequently the storage requirements is large for high spatial resolution 3D inversions if these products are required to be stored. Another drawback of the summation approach is the algorithmic scaling. If the domain contains $N \times N \times N$ voxels, we are required to perform $O(N^3)$ operations per point of interest $s$. Hence the increasing the number of gravity stations which are used as data in the inversion increases the computational cost of the method.

An alternative to the summation approaches is to solve a Poisson problem for the gravitational potential and then compute the gradient of the resulting potential to obtain the gravity. Using such a PDE based forward model has the advantage that the operator $F$ is sparse, and there the computational cost is independent of the number of gravity stations used in the inversion. Recently, Cai & Wang (2005), proposed a more accurate boundary condition to circumvent the need to try to impose that the potential should vanish at infinity. These authors utilised a finite element discretisation as it provided high geometric fidelity to define their gravity anomaly. In contrast Farquharson & Mosher (2009), used a finite domain with zero Dirichlet boundary conditions on the potential and used a finite difference discretisation. Whilst both of these forward models do not have an algorithmic scaling dependent on the number of gravity stations, the time required to obtain the potential field using their iterative solvers is dependent on the grid resolution used to discretise the subsurface.

Here we describe a parallel finite element based forward model to solve the Poisson problem. This method incorporates several new features. Firstly it permits locally refined meshes to be used near the gravity anomaly and in the regions of free space, the grid resolution is quite coarse. We also incorporate the near-field boundary conditions of Cai & Wang (2005), thus improving the approximation that the potential should be zero at infinity. In addition, we introduce a second order accurate recovery procedure to compute the gravity field from the potential. We also introduce an optimal multilevel preconditioner to solve the Poisson problem. This feature is necessary to ensure the forward model is remains efficient for high resolution 3D inversions. We demonstrate that the preconditioner is robust with respect to the aspect ratio of the elements used in the grid and that the solution time scales linearly with respect to the number of elements in the domain. The accuracy, speed and scaling with respect to the number of elements and the number of gravity stations of the new forward will be compared with a classical closed form summation forward model.

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1.26

The Fribourg Structure and Fribourg Zone: an Active fault system?

or

The Rösti Graben – Geologic evidence!

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Located between the Jura mountains to the North and the Alps to the South the larger Fribourg region has been, possibly since Oligocene, and is still subjected to compressive stresses resulting from the alpine orogenic processes. The subsurface geology of the Fribourg area is basically a layer cake with 3 main levels: the Tertiary Molasse sediments overlying the Mesozoic units detached along a basal décollement in the Triassic evaporites, and below the Basement s.l. including possible Permo-Carboniferous graben structures, and Paleozoic rocks.

In the Fribourg area we observe a deviation from this general trend with folds, as well as major faults trending N-S to NNE-SSW. This extends some 17 km to the North and 10 km to the South of the city of Fribourg. Around Fribourg its width in an E-W direction is about 10-12 km. This whole tectonic zone is called the Fribourg Structure (FS) and its central part forms the Fribourg syncline (known from surface data). It has been suggested that recent earthquakes align along a more or less N-S oriented line, running just east of the city of Fribourg (Swiss Seismological Service). This alignment is called a lineament and was dubbed the Fribourg Zone (FZ) and corresponds to the eastern edge of the Fribourg Structure.

The regional tectonic elements result from a complex sequential and spatial evolution combining extensional and strike-slip faults as well as thrusts and folds. The deformation affects the basement and the cover series to different degrees. During the foreland evolution and contemporaneously to the fold-and-thrust development of the Jura (classically given between 15 and 4 My), the Molasse basin of W Switzerland was detached above the Triassic evaporites and transported to the N by some 25km ("Fernschub"). During this period we see the formation of a series of thrusts and related folds with a general NE-SW alpine trend that started out as gentle folds above salt pillows. Some zones, such as in the Tschugg and Hermigen area, form complex structures with frontal ramps and N-S trending lateral ramps with a strike-slip motion component at their western edges. In the Fribourg area a graben-like structure associated with salt migration deforms the overlying sedimentary cover to develop a N-S oriented depression. This structure is associated with a series of normal faults developing at the eastern and western edges. Subsequently, as a result of alpine compression, the sedimentary cover deforms in a strike-slip regime. This causes the faults at the eastern edge of the graben to be reactivated. The faults are reactivated as an N-S en-échelon Riedel shear system. Comparing the model to the present-day distribution of earthquake activity suggests that the southern portion of the FZ is an “active fault”.

Reinterpretations of reflection seismic data (440 km of lines in Fribourg area interpreted by B. Meier - InterOil, basinwide interpretation by A. Sommaruga, U. Eichenberger - Inst. Géophysique Lausanne Project with Swiss geophysical Comission) demonstrate that the faults presently active in a strike-slip mode, are clearly seen only found in the sedimentary cover and they do not extend into the basement. The new interpretation also confirms that faults are of modest dimension and arranged as a Riedel shear system.

The Fribourg Structure and the Fribourg Zone should be considered in the broader context of the deformation of the Molasse foreland basin. Unlike the situation further east where the foreland basin is in a general state of extension, the western Swiss Molasse foreland basin is in a compressional tectonic setting. This is clearly substantiated by the numerous fold and thrust structures that develop between Bern and the western termination of the Basin SW of Geneva, in the Chambéry area. In this whole zone the Molasse basin is not acting as a foreland basin but it is behaving as a wedge-top basin in the south and southeast, behind the Jura Mountains whose northernmost external thrust represents the present orogenic front.

In this framework the Molasse basin in the Fribourg - Lausanne area appears to be deforming at present mainly by large strike-slip fault zones. Several major zones form a pattern of conjugate fault systems or corridors that allow the basin to deform and shorten. Each of these corridors corresponds to a Riedel shear systems developing its own sets and subsets of fractures. Two main directions are observed: N-S sinistral and NW-SE dextral.
Structural map of the larger Fribourg area. Based on a compilation of existing surface data (mainly maps) and a new interpretation of reflection seismic data. Seismicity from SED catalogue; deep oil exploration wells are indicated (red circle and cross).
1.27

Glacially enhanced fluvial erosion and rock uplift in the Swiss Alps

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The Swiss Alps are one of the most thoroughly studied mountain landscapes in the world. Nearly two centuries of intensive geologic research has lead to an unparalleled database of bedrock properties, erosion rates, and geomorphic and tectonic parameters. One result of these data is an ongoing debate as to the meaning of apparent correlations between surface denudation and modern rock uplift.

In the simplest case the Swiss Alps can be considered an isostatically compensated, non-convergent orogen. Theory suggests that rock uplift rates should be positively correlated with denudation rates (with a coefficient of 0.8) for such a system. Assuming that this is true, the next major challenge is to search for process linkage: denudation is a very broad term, encompassing such varied processes as chemical weathering, soil creep, and rockfall. Therefore, simply claiming that rock uplift is driven by denudation provides us with little additional insight.

Here, we show how individual fluvial and hillslope processes contribute to the denudational budget of the Alps, and provide a causal link between surface processes and resultant rock uplift rates. An analysis of stream channel steepness shows that oversteepened streams are associated with glacially perturbed landscapes (Figure 1; Norton et al., 2010a). These glacially impacted regions also exhibit up to 10-fold higher denudation rates than adjacent fluvial basins (Norton et al., 2010b). This results in a spatial focusing of erosion which elevates fluvial incision rates, driving associated hillslope responses such as landsliding and rockfall, which are intimately tied to the underlying lithology. Norton et al. (2010a) show that channel steepness is a function of bedrock erodibility for steady-state streams, but that this correlation breaks down in the non-steady state case, where channels are oversteepened, regardless of bedrock erodibility. Likewise, lithologies such as the schists of the Bündnerschiefer, are loci for enhanced landsliding and rock uplift.

Finally, if there is no longer active convergence in the Swiss Alps, one must question the mechanism which maintains both denudation and rock uplift at such high rates. We postulate that the effect of repeated Pleistocene glacial perturbations has been the continual renewal of transient river segments, resulting in rapid, focused fluvial incision, enhanced landsliding on adjacent slopes, and a concomitant increase in rock uplift due to isostatic compensation to the erosional mass loss.

![Figure 1. Patterns of LGM ice thickness and over-steepened streams (individual segments in red, and density of streams in black) in Switzerland (figure modified after Norton et al. (2010a)).](image)

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1.28

The Canavese Fault west of Valle d’Ossola

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The Periadriatic Fault system has had an important influence on Neogene Alpine kinematics and is commonly taken to have partly accommodated crustal convergence between the European and Apulian plates in the Oligocene to Early Miocene. The total amount of the dextral strike-slip component on this major fault is controversial, ranging from a few tens of kilometres to many hundreds.

Fieldwork along the Canavese Fault (i.e. the Periadriatic Fault west of Lago Maggiore) has corroborated the results of earlier studies (Schmid et al. 1987, 1989) that the Canavese Fault comprises several greenschist-facies mylonite belts. These belts accommodated different relative motions between the Southern and Penninic Alps at different times.

In the Valle d’Ossola, the Canavese Fault comprises mylonites with N-side-up shear sense mostly derived from the Sesia Zone and mylonites with a dextral shear sense mostly derived from the Ivrea Zone (see also Schmid et al. 1987). In some places, the dextral mylonites have a strong S-side-up component of displacement. The N-side-up mylonite belt appears to be consistently overprinted by the dextral belt. West of Valle d’Ossola, the volumes of both the dextral and the N-side-up mylonites diminish rapidly. Toward the west, they can be traced until Valle Strona and Valle Mastallone, respectively. From Valle Strona to the west, the N-side-up mylonites are paralleled by a belt of greenschist-facies S-side-up mylonites to the north which generally have a sinistral displacement component. The age relation between the N-side-up and S-side-up mylonites could not yet be determined. Between Valle Mastallone and river Dolca in Valle Sessera, another belt of S-side-up mylonites, in this case with a dextral strike-slip component, is developed within the Ivrea Zone. This mylonite belt is identical with mylonite belt 1 of Schmid et al. (1989; also mapped by Handy et al. 2005) except that we interpret mylonites of belt 2 of Schmid et al. (1989) in the Valle Sessera to belong to the same belt. The volume of Canavese Fault mylonites decreases toward southwest. In the Valle Sessera and further southwest, the thickness of Canavese mylonites does not exceed a few tens of metres.

Since the dextral mylonite belts mentioned above are not continuous along the Canavese Fault, strike-slip displacement in the order of 100 km, as postulated by various authors, can only be explained if displacement was transferred away from the Canavese Fault into the Penninic domain. Splays branching off the Canavese Fault, as postulated by Handy et al. (2005), may provide the explanation for the eastward accumulation of dextral displacement between the Western and Central Alps with respect to the Southern Alps (Schmid et al. 1989, Handy et al. 2005, Pleuger et al. 2008). These splays need verification because the assumption of dextral displacement on the order of 100 km requires a set of continuous faults that were active at the same time.

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1.29

B-type Olivine LPO in the Ronda Peridotite (Spain): Evidence of high-Strength sub-Continental Mantle

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Experimental rheological laws of olivine predict the presence of high-strength lithosphere mantle beneath the continental crust (Brace & Kohlstedt, 1980). Analogue and numerical models have shown that such a stiff uppermost mantle - stronger than the crust - is required to form a subduction or a narrow continental rift (Gueydan et al., 2008). In contrast, based on “indirect” geophysical observations, recent studies concluded for a sub-continental mantle weaker than the crust (Thatcher & Pollitz, 2008). In this study, we document data of olivine Lattice Preferred Orientation (LPO) in the Ronda continental peridotite (southern Spain) that provide new constraints on the mantle strength through “direct” observations. The Ronda massif exposes 300 km² of sub-continental peridotites that were exhumed in the internal Betics during the Oligocene-early Miocene. During their exhumation, they suffered intense ductile deformation that formed a kilometre-scale mylonite beneath a strongly thinned continental crust. This mylonite of extremely condensed peridotites deformed at about 850-900 °C during decompression from 18 to 10 kbar (Morishita et al., 2001). Across this domain, olivine LPOs revealed changing slip system of dislocations from A-type fabric ((010)[100]) to B-type fabric ((010)[001]) toward the overlying crust. Based on recent experimental data (Jung et al., 2006), A-type fabric implies low-stress deformation of anhydrous olivine (< 400 MPa), while B-type fabric characterizes olivine deformation at more than 400 MPa of differential stress, regardless of the water content. The occurrence of high-stress deformation in the sub-crustal Ronda peridotite confirms therefore the prediction of high-strength mantle beneath the continental crust. Nonetheless, by comparing the deformation conditions of the Ronda mylonite (850 °C and 400 MPa) with the predicted strength of the mantle lithosphere, these results suggest that olivine rheological laws largely underestimate the «real» strength of the sub-continental mantle.

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1.30

Low-temperature thermochronological constraints on the Miocene exhumation of the Adamello Complex, Southern Alps, Italy

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The Adamello Complex is the largest of the Periadriatic intrusions and is located at the intersection of the Periadriatic Fault System (locally called the Tonale line) and the South Giudicarie line. More than seven kilometers of overburden has been removed since its emplacement in the late Eocene-early Oligocene and modern overall relief is over 2 km. Major rivers which dissect the complex flow into overdeepened valleys inferred to be areas of maximum incision from the Messinian Salinity Crisis (MSC). This makes it an ideal location to determine the role and magnitude of inferred tectonic events (Giudicarie phase shortening in the late Miocene) and superimposed erosional events driven by climatic or other external environmental conditions (MSC and Neogene glaciation) as drivers of near surface exhumation.
Low-temperature thermochronometers, such as, apatite (U-Th-Sm)/He dating (AHe) and apatite fission-track dating (AFT), constrain near-surface (<5 km) exhumation rates that can be used to characterize climate or tectonic forcing. In this study we present AHe and AFT ages for samples collected in the two largest valleys of the Adamello Complex. The ages determined in this study span the Miocene and display a normal age-elevation relationship, where age increases with elevation. All AFT ages along with the high elevation (3600-2700 m) AHe samples record early to mid-Miocene ages, while samples located below 2700 m record nearly identical AHe ages, within error, of 6.5±1 Ma. This pattern reveals the possible base of an exhumed AHe partial retention zone located at a modern elevation of ~2700m, which suggests that a minimum of 3-4 km of exhumation has occurred since ~8 Ma.

The fast cooling of the low elevation samples as recorded by their AHe ages indicate that at least 2 km of rock was exhumed rapidly between 8-6 Ma. The magnitude and timing of this event suggested by our results constrain a period of transpressional activity along the South Giudicarie line and Val Trompia thrust inferred from thermal modelling of fission-track data from the area and structural evidence (Castellarin et al., 2006; Martin et al., 1998). Furthermore, the ages were modelled using Pecube (Braun, 2003), a 3-D heat conduction model including topographic relief and erosion and the recently developed GLIDE program (Fox et al., 2010), which extracts exhumation rates from thermochronological data. Both models confirm a rapid increase in exhumation rates at ~8 Ma and continuing until ~6 Ma.

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1.31

Influence of continents in mantle convection models with self-consistent plate tectonics

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It is now well accepted that mantle convection and plate tectonics form an integrated system and cannot be treated independently. Although this is a promising improvement in understanding Earth, there is still a striking feature, which is nowadays not yet included in this integrated system, namely the existence of a lithospheric heterogeneity - in other words the difference between oceans and continents.

The present study focusses on the effect of continents in a model of self-consistent plate tectonics in spherical geometry. As a simplification these continents are realized as strong cratons with homogeneous composition and they differ from the rest of the mantle in buoyancy and rheology. In contrast to many former studies where continents are idealized as rigid and/or immovable units, we treat continents in the same manner as normal mantle, but with different physical properties. Numerically a tracer approach is used, which allows more consistent movement and deformation of the continents.

It has been shown before that continents might have a first-order effect on the dynamics of the Earth as they might modulate convective wavelength, surface heat loss and - due to thermal insulation - the internal temperature. Increasing the latter causes a decrease in convective stresses and we studied how this effect strengthens the lithospheric lid, what finally leads to a transition from mobile lid to stagnant lid convection. Existence and timescale of this transition depend on the initial strength of the lithosphere and are most sensitive to internal temperature variations, but less sensitive to relative continental buoyancy.

The mentioned transition will be studied into more detail. A question of particular interest is, if the system behaviour changes, if the continents are no longer embedded in the thermal boundary layer. For answering this question it is necessary to modify the rheology of the continental material, namely to consider a viscosity, that depends on composition, and to make sure that continents are initially cold.
1.32

Accretionary wedge dynamics: A numerical approach

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Subduction accretion adds material to the front of a convergent margin by thrusting and stacking sediment onto the subducting plate. Accretionary wedges have been the focus of much investigation because they provide key information on sediment deformation in a generally submarine and tectonically active environment. Because most of the modern accretionary wedges are not exposed on land (Barbados, Costa Rica, Nankai, Gulf of Cadiz, Eastern Mediterranean), their large-scale characteristics are interpreted from seismic profiles (e.g. Grando and McClay, 2007), and their bulk behaviour and growth is commonly simulated in analogue experiments (e.g. Smit et al., 2003). Based on a wealth of data, principally due to Oceanic Deep Sea Drilling, we believe that accretionary wedges form over a major décollement. Off-scaping removes material from the subducting plate and the wedge grows both vertically and horizontally by addition of oceanic sediment and shallow crustal material.

An important characteristic of accretionary wedges is the contemporaneous activity of deformation and sedimentation, which leads to the formation of growth structures (Figure 1).

![Figure 1. Interpreted seismic profile of an imbricated fan segment offshore Makran from Grando and McClay (2007) indicating progressive unconformity development on the back limb of growing fault-propagation folds. Vertical exaggeration is ~2, as 1 s (TWT) is ~1.1-1.2 km depth.](image)

One of the biggest and still active accretionary complex is Makran, in Iran and Pakistan. The essentially Eocene–Holocene wedge results from the still on-going subduction of the oceanic lithosphere flooring the Gulf of Oman. The present shoreline follows a complex fault zone that approximately separates an active, submarine and frontal southern half from a less active, exposed northern half. Water provided by dewatering of the accreting sediments apparently lubricates the basal décollement.

The influence of surface processes on thrust wedges has drawn increasing attention during recent years: Experimental studies have tested the effects of syntectonic erosion and sedimentation on the mass distribution in the wedge and thus its geometry and evolution (e.g. Barrier et al., 2002). However, these models do not satisfactorily explain the geometry of growth strata cropping out in Makran, their relation to thrusting, and their influence on wedge dynamics. One reason is that most current models of thrust wedges are derived from purely frictional experimental studies in which syntectonic erosion and sedimentation are included either as a predefined temporal or continuous mass redistribution or as a static system of evolving thrusts and growing folds.

Fieldwork on the Iranian Makran led us to identify several types of growth structures in the Miocene-Pliocene sequences, documenting complex relationships between sedimentation and regional tectonics. From our field observations we noticed that these growth structures and the related thrusts and folds are also not satisfactorily explained by existing numerical models.

We present results of new 2D numerical models in which we test the influence of sedimentation in thrust wedges and the interplay between thrusts, folds and growth strata both at wedge scales and at the scale of single structures (Figure 2). We use a visco-elastoplastic finite element code to simultaneously take the brittle overburden and the ductile substratum into account, which in the Makran is formed by shale-rich (at least initially) water-saturated soft units like marls.
REFERENCES

1.33
Tectono-thermal evolution of the Atlas system (SW Morocco), insights from low-temperature thermochronology and Raman spectroscopy on carbonaceous material
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In Morocco, the High and Middle Atlas of Morocco are intra-continental fold-thrust belts situated in the southern foreland of the Rif orogen (Fig. 1). It is a key natural laboratory because it 1) is the southern and westernmost expression of Alpine-Himalayan orogeny, and 2) possibly encompasses Pre-Cambrian to recent evolution of the region. Phases of shortening and exhumation of this orogen remain however ill constrained and the few available quantitative data do not allow the present-day high topography (over 4000m) to be explained. In order to put constrains on the recent orogenic growth of the Atlas system, we investigated the temperature-time history of rocks combining extensive low-temperature thermochronological analysis (Fission tracks and [U-Th]/He on zircon and apatite) and peak temperature estimation by Raman spectroscopy of carbonaceous material (RSCM) and U-Pb ages. The target area is a NE-SW oriented transect crossing the different structural segments of the western Atlas away from present-day fault systems (Fig. 1). Results are much contrated from one domain to the other. Pre-Cambrian bedrocks from the Anti-Atlas domain yield old Fission-Track ages on zircon (340-300 Ma), apatite (180-120 Ma) but also U-Th/He (150-50 Ma) still on apatite. These datasets are interpreted, with
the help of thermal modelling, to record passive margin up and down movements during the break-up of the Pangea. U-Th/He pair dating on both apatite (80-55°C) and zircons (200-160°C) minerals are much younger in the High-Atlas once the Tizi N’Test Fault System (TNT), or SAF (Fig. 1) passed to the north, ranging between ~35-5 Ma and 85-30 Ma respectively. Similarly, maximum peak temperatures vary across the TNT, with maximum temperatures of 500-450°C in the axial zone and less than 250-200°C in the Souss plain to the south. Once all datasets combined, they indicate that uplift occurred in the Axial Zone in the Oligocene due to tectonic inversion and crustal shortening and remain constant since allowing a 6-7 km thick pile to be eroded. Low-thermochronological analyses have also been performed on Cretaceous deposits in the region. Results indicate that these deposits have been reset to temperatures greater than 80°C. This suggests that a post Cretaceous sedimentary pile of at least 3 km in thickness is missing, and as a result that a 3-4 km thick pile of substratum have been eroded in the Axial Zone. Our extensive thermochronological dataset provide for the first time constraints that evidence heterogeneous exhumation history across and along the chain. All these constraints are put together with structural, geochemical and geophysical informations to discuss the recent tectono-thermal evolution of the Atlas system in the frame of the Africa-Europe convergence and thinning of the lithosphere.

Figure 1. Top: Schematic map of northern Africa showing the main domains in Morocco, i.e. from north to south Rif-Tell, Meseta (ME), Middle-Atlas (MA), High-Atlas (HA), Anti-Atlas (AA), Tindouf Basin (TB) -Saharan Domain (SD) and Reguibat Shield towards the West Africa Craton (WAC) and finally the Tarfaya-Dakhla Basin (TDB) to the SW along the Atlantic Ocean. The studied area (red rectangular) south of Agadir corresponds to the western segment of the Atlas system than encompasses Precambrian inliers, i.e. the Ifni (IF), Kerdous (KE) and Igherm (IG) within the Paleozoic Anti-Atlas domain. SB: Souss Basin. Ag.: Agadir. Thin dashed blue line: corridor for <110 km thick lithosphere (Fullea et al., in press). Bottom: Topographic profile across the region against the strike of the orogen (x10 vertical exaggeration) - see thick dashed red line for location, horizontal and vertical axis in kilometres.
1.34

Strain accumulation during basal accretion – case study Suretta nappe (eastern Switzerland)

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Using a field-based approach we investigate basal accretion processes in the Alps to better understand the stacking of crystalline basement nappes as observed in the core of many orogens. In eastern Switzerland, the Suretta nappe comprises a stack of lithospheric slices derived from the Briançonnais domain and assembled in a south-dipping subduction zone during the Cenozoic orogenic cycle. The present axial plunge of about 30° towards the ENE exposes the basal thrust of the Suretta nappe over tens of kilometres and provides nearly continuous outcrop from bottom to top of the nappe.

In order to understand fold-thrust relationships in the Suretta nappe, a partial retro-deformation was performed, because the Eocene top north directed stacking (Ferrera phase after Milnes & Schmutz, 1978; Schmid et al, 1997) predates a phase of backfolding (Niemet-Beverin phase).

Emphasis was laid on the frontal part of the nappe composed essentially of late to post-Variscan intrusive rocks of the Rofna porphyry complex. Detailed structural mapping combined with strain analyses using the center-to-center (Fry) method based on the distribution of K-feldspar clasts (Genier and Epard, 2007) yield different strain patterns of the porphyry.

In the lower and interior parts of the nappe, weakly to undeformed boudins are generally surrounded by L-tectonites indicating WSW-ENE stretching; foliated equivalents reveal various strain intensities. The upper part of the nappe which was strongly affected by retro-shearing and backfolding generally shows higher strains. In this part of the nappe, the dominant WSW-ENE constrictional strain is overprinted by a more N-S directed stretching component. This leads to an oblate finite strain ellipsoid.

Mylonites were not only detected at the base of the Suretta nappe, but also at the base of internal thrust slices overlying strongly deformed autochthonous Triassic sediments (“nappe separators”). These mylonites bear NW-SSE trending stretching lineations, which are related to Ferrera phase nappe stacking. Despite the fact that shear sense indicators are generally rare, a top-to-the NNW directed transport can be assumed. Thrust-related deformation took place in a temperature regime of about 400°C where quartz deformed by dislocation creep and feldspar was the stronger mineral. Intercalations of Triassic sediments in the upper parts of the nappe that could be interpreted as isoclinal folds at first sight seem to be influenced by thrust tectonics as well.

Figure 1. Finite strain ellipses in the Suretta nappe (cross-sectional view).

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1.35

**Structural and cooling history of the Eastern Pelagonian metamorphic core complex (northern Greece)**

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The Pelagonian Zone in continental Greece is the westernmost unit of the Internal Hellenides and is characterized by a structural and topographic high trending approximately NNW-SSE. We present mapping, petrographic, structural and thermochronologic data that are evidence of a metamorphic core complex in the eastern part of the Pelagonian. The area lies north and east of the Aliakmon River artificial lake (between the village of Servia in the west and the village of Kolindros in the east). The denuded metamorphic dome is about 20 x 15 km with the long axis striking NNW-SSE.

The main lithologies (gneiss, marbles and amphibolites) show a shallow-dipping foliation whose bending defines the dome. On the foliation plane aligned micas and amphiboles, and elongated quartz and feldspar form a pervasive lineation that trends SW-NE. The systematic record of asymmetric structures in the XZ-plane of finite strain ellipsoid indicates two senses of shear: (i) a regional top-to-the-SW sense of shear (Direction: 243°±25; Plunge: 8°±15) characterized by a strain gradient from protomylonite to ultramylonite, and related to recumbent, isoclinal and occasional sheath folds; (ii) a top-to-the-E sense of shear (Direction: 88°±20; Plunge: 11°±16) found in narrow (20 to 100 m) low angle shear zones located on the eastern flank of subdomes. In the footwall of the top-to-the-E detachments, migmatitic orthogneisses and amphibolites vary from metatexite, with partial melting associated with folding, to diatexite. Leucosomes cut the main foliation. Thus, the metamorphic peak and the main fabric-forming event are coeval.

Zircon fission-track ages of about 24 Ma on both sides of the top-to-the-E shear zones show that the ductile fabric is older than the late Oligocene. Fission-track data on apatites indicate cooling at <110°C during the early to middle Miocene. These cooling ages show that extensional tectonics in the Pelagonian were contemporaneous with the Aegean extension (Mykonos, Naxos, etc.).

1.36

**Quantitative comparisons of analogue thrust wedge experiments**

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Analogue (sandbox) experiments have a long history of modelling orogenic wedge processes, examining, for example, out-of-sequence thrusting, surface slope evolution and the roles of basal friction or surface processes. However, as for all models, their results bear a signal of the initial conditions, the choice of materials, the modelling apparatus and the technique of building model. This may make it difficult to compare model results directly. In order to evaluate the variability among models and to appraise the reproducibility and limits of interpretation, we have performed a direct comparison of experimental results of 15 analogue modelling laboratories for three different thrust experiments. Our quantitative analysis of the results has direct implications for comparisons between structures in analogue models and natural field examples.

All laboratories used the same frictional analogue materials (quartz and corundum sand) and model-building techniques (sieving rate, sieving height and levelling). Although each laboratory used its own experimental apparatus, the same type of self-adhesive Alkor foil was used to cover the base and the four vertical walls of the experimental apparatus in order to guarantee identical shear stresses at the boundaries. Temperature and humidity was not controlled and was found to have varied between laboratories.

Three experimental set-ups using only brittle frictional materials were examined (Fig. 1). In each of the three set-ups, the model was shortened by a vertical wall, which moved with respect to the fixed base and the three remaining sidewalls. The minimum width of the model (dimension parallel to mobile wall) was prescribed at 25 cm. In the first experimental set-up (experiment 1A, Fig. 1), a quartz sand wedge with a surface slope of ~20° was pushed by a mobile wall. All models
conformed to the critical taper theory, maintained a stable surface slope and did not show internal deformation. In the next two experimental set-ups (experiments 1B and 2, Fig. 1), a horizontal sand pack consisting of alternating quartz sand and corundum sand layers was shortened from one side by the mobile wall. In experiment 2 a thin rigid sheet covered part of the model base and was attached to the mobile wall (i.e. a basal velocity discontinuity distant from the mobile wall).

In experiment 1B a basal rigid sheet was absent and the basal velocity discontinuity was located at the mobile wall. In both experiments, models accommodated initial shortening by forward- and backward-verging thrusts. In all experiments, boundary stresses created significant drag of structures along the sidewalls. We therefore compared the surface slope and the location, dip angle and spacing of thrusts in sections through the central part of the model.

![Diagram of experimental set-ups](image)

**Fig. 1.** Experimental set-ups used in our analogue model comparisons

All analogue models show similar cross-sectional evolutions demonstrating reproducibility of first-order experimental observations. Forward shear zones in the models develop at Mohr-Coulomb dip angles. However, the surface slopes of experiments 1B and 2 do not reach a critical taper. In addition, we find significant along-strike variations of structures in map view, highlighting the limits of interpretations of analogue model results. These variations between models may be related to model width, differences in laboratory climatic conditions and/or “the human factor”. The latter may result in small differences in model building techniques and therefore in models with slightly heterogeneous layer densities, which would affect the mechanical properties of the granular material.

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Seismic Atlas of the Swiss Molasse Basin: two example transects across the western and the eastern parts.

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A regional seismic synthesis based on the interpretation of reflection profiles from the oil industry was conducted on the Swiss Plateau as a multiyear project of the Swiss Geophysical Commission. It will result in the publication by swisstopo of a “Seismic Atlas of the Swiss Molasse Basin” that will include more than 20 large printed plates. The interpreted seismic lines (263 lines representing a total of 4358 km) cover the entire Swiss Molasse Basin from Canton Geneva to Lake Constance. These lines represent about 1/3 of all the ones shot in Switzerland since the sixties into the nineties. The western part of the Molasse Basin is especially well covered because of a larger number of surveys carried out there (especially in the Cantons of Vaud and Fribourg). In eastern Switzerland, less surveys resulted in broader seismic line spacing. More than 20 deep wells helped calibrating the seismic interpretation.

Only few seismic lines are publicly available. They include a small number of very deep reaching seismic lines, along two Alpine traverses, from a Swiss National Science Foundation project (NPF20), oil industry lines older than 10 years collected in Canton Vaud, lines published by NAGRA, lines published in scientific papers and 52 oil industry seismic lines deposited in 1992 at the geological archive of swisstopo. The public lines all together add up to a 15% of the total number of 2D lines ever shot in Switzerland. The rest is confidential.

The seismic interpretation focussed on Mesozoic units and faults affecting them. It took into account larger features within the pre-Mesozoic and Tertiary units and was carried out entirely on paper seismic sections (at 1:25'000 or 1:20'000 scale). Eight seismic horizons were interpreted and correlated between intersecting lines: Near Base Tertiary, Near Base Cretaceous/Near Top Late Malm, Intra Early Malm, Near Top Dogger, Near Top Liassic, Near Top Late Triassic, Near Top Early Triassic and Near Base Mesozoic. The horizons were digitized and introduced in a GIS data base. The digitized horizons were first adjusted to a common reference level of 500 m. Because of differing parameters used by the several companies that processed the data some two-way travel time (TWT) offsets (so-called "misties") remained between seismic sections of different surveys. Misties were reduced with a procedure that minimized their mean values over the entire data set. For each interpreted seismic horizon a TWT map was computed by kriging. The TWT maps were converted to depth using seismic velocity maps elaborated from well data. From the depth maps, vertical thickness maps were computed for the following units: Quaternary and Tertiary, Cretaceous, Late Malm, Early Malm, Dogger, Liassic, Late Triassic, Early Triassic.

In addition to the TWT-, velocity- and depth maps, the Seismic Atlas will contain 15 transects across the Swiss Molasse Basin. Thirteen transects are dip sections at 1:80'000 scale extending from the foot of the Jura Mountains to the Subalpine Molasse and the Alpine nappes. Two transects are strike sections that extend across the entire Swiss Molasse Basin from Canton Geneva to Lake Constance at a scale 1:250'000 with vertical exaggeration (1:80'000 in vertical scale). Each transect plate includes three sections: on top, the seismic profile (in TWT) that is a composed seismic section without interpretation in order to display the quality of the available seismic data; in the centre, the geological interpretation superimposed on the seismic section (in TWT) with the wells and only seismically supported elements (horizons and faults) within the Tertiary, the Mesozoic and the Pre-Mesozoic units; at the bottom, the depth converted seismic section is shown with additional features (conceptual faults and horizons) based on geological information (geological maps, well reports, published papers, confidential reports). The identified seismic reflections are differentiated in three quality classes: well defined, fairly well defined and poorly defined. A similar classification is introduced for faults but with only two classes: well defined and fairly well to poorly defined. All these criteria apply to the Tertiary and Mesozoic units, whereas different quality classes are defined in the pre-Mesozoic (reflective, intermediate and non-reflective zone), because of the poorer quality of the seismic data in this unit.

The poster will present two selected transects, one from the eastern and one from the western part of the Swiss Molasse Basin. These two transects highlight the stratigraphical and structural differences between the western and the central to eastern parts of the basin. Based on these transects, new insights and important conclusions can be drawn despite a somewhat unevenly distributed data set (looser grid in the central and eastern parts). The western area, comprising the Cantons of Geneva, Vaud, Fribourg and parts of Canton Bern, displays thicker Mesozoic strata, thicker Triassic evaporite sediments and more Mesozoic normal, reverse and tear faults than the central and eastern parts. Little evidence is found for faults extending over long distances. Rather, en echelon fault patterns appear to be the dominant structural style. In the western most part, structures in the Mesozoic sequence are characterized by generally NE-SW oriented synclines and anticlines of low amplitude, with cores of Middle-Early Triassic evaporite layers. The latter represent the detachment zone of the western
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1.38 Modelling the thermo-chemical evolution of the interiors of Earth, Venus, Mars, Mercury and super-Earths

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The latest generation of the global 3-D spherical convection model StagYY [Tackley, PEPI 2008] allows the direct computation of a planet’s thermo-chemical evolution, including self-consistent lithospheric behavior (e.g., rigid lid, plate tectonics, or episodic plate tectonics [van Heck and Tackley, GRL 2008]), chemical differentiation induced by melting, large viscosity variations, a parameterized core heat balance, and a realistic treatment of phase diagrams and material properties. Global models allow the computation of planetary secular cooling including prediction of how the core heat flux varies with time hence the evolution of the geodynamo, and possible transitions in plate tectonic mode. Modern supercomputers and clusters allow increasingly higher resolution, with up to 1.2 billion unknowns possible on only 32 dual-processor nodes of an opteron cluster. In ongoing research, this tool is being applied to understand the evolution of Earth, Mars, Venus, Mercury, and super-Earths. Studying several bodies using an integrated approach facilitates a more systematic and holistic understanding of planetary behaviour both inside and outside our solar system.

With our Venus models we are studying the modes of heat loss, the origin of the inferred surface age and understanding the admittance (gravity/topography) ratio. Of particular interest is whether a smooth evolution can satisfy the various observational constraints, or whether episodic or catastrophic behaviour is needed, as has been hypothesised by some authors. Simulations in which the lithosphere remains stagnant over the entire history indicate that over time, the crust becomes at least as thick as the mechanical lithosphere, and delamination occurs from its base. The dominant heat transport mechanism is magmatic. A thick crust is a quite robust feature of these calculations. Higher mantle viscosity results in larger topographic variations, thicker crust and lithosphere and higher admittance ratios; to match those of Venus, the upper mantle reference viscosity is about $10^{19}$ Pa s and internal convection is quite vigorous. The most successful results in matching observations are those in which the evolution is episodic, being in stagnant lid mode for most of the evolution but with 2-3 bursts of activity caused by lithospheric overturn. If the last burst of activity occurs ~1 Ga before present, then the present day tends to display low magmatic rates and mostly conductive heat transport, consistent with observations. In ongoing work we are examining the effect of crustal rheology and a more accurate melting treatment.

Our Mars models [T. Keller and P.J. Tackley, Icarus 2009] show that with an appropriate viscosity profile, convection rapidly develops a ‘one ridge’ planform consisting of a single ridge-like upwelling and small-scale downwellings below a stagnant lid, and that this produces a dichotomous crustal distribution that bears a striking first-order resemblance to the crustal distribution on Mars. The actual boundary of the crustal dichotomy on Mars is not hemispherical but rather like the seam on a tennis ball, and this is reproduced by our models, with the highland region being located above the upwelling. Furthermore, the elevation difference between the highland and lowland regions is very similar to that on Mars, although the average crustal thickness is higher than thought to be appropriate for Mars. Melting is found to have a dramatic influence on thermal evolution particularly during the early stages.

Due to the absence of an atmosphere and proximity to the Sun, Mercury’s surface temperature varies laterally by several 100s K, even when averaged over long time periods. The dominant variation in time-averaged surface T occurs from pole to equator (~225 K). Here we demonstrate, using models of mantle convection in a 3-D spherical shell, that this stationary lateral variation in surface temperature has a small but significant influence on mantle convection and on the lateral

Swiss Molasse Basin. Tertiary sediments within the Plateau Molasse are slightly folded (very low amplitude) requesting a detachment horizon at the base of the Tertiary unit or within shaly beds of this unit. In the Subalpine Molasse, folds are related to thrust faults rooting at the Base Tertiary strata.

By contrast to the western area, Cretaceous unit layers were not preserved in the central and eastern areas. There, Triassic evaporites are reduced to a few tens of meters in some locations. Below the Plateau Molasse, a few normal or reverse faults occur. They represent the major structures within the Mesozoic beds. However, below the Subalpine Molasse and the Alpine nappes, south of Lake Lucerne and Lake Zürich, many more of such faults are observed within the Mesozoic units. At Tertiary level, the strata are displaced along thrusts and back-thrusts, representing a triangle zone. These faults root in a detachment level within the Tertiary sequence. In the easternmost part of the Swiss Molasse Basin, we observe normal faults cutting through Mesozoic and Palaeozoic units. This area is (was) clearly under extension. The transition from the eastern to the western Molasse Basin structures takes place in Canton Bern. Unfortunately, in that area the density of data is low and the quality of seismic lines is poor.

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variation of heat flux across the core-mantle boundary (CMB). We evaluate the possible observational signature of this laterally-varying convection in terms of boundary topography, stress distribution, gravity and moment of inertia tensor.

The discovery of extra-solar planets with terrestrial composition and sizes up to twice that of Earth, so-called “super-Earths”, has prompted interest in their possible mantle dynamics and evolution. The pressure at the core-mantle boundary (CMB) of a 2’ Earth-sized super-Earth is about eight times the pressure at Earth’s CMB, which has a strong effect on physical properties such as thermal expansivity, diffusivity and viscosity. The mantle of such a super-Earth would be made mostly of post-perovskite (PPv), which has different physical properties than perovskite, the major mineral of Earth’s lower mantle. Here we use the newly-computed rheological parameters for PPv, computed using density function theory [Ammann, Brodholt and Dobson, 2008] in simulations of super-Earths of up to twice Earth size. The models assume a compressible anelastic approximation that includes the depth-dependence of material parameters. Rheological parameters for minerals other than PPv are based on those for perovskite. Plastic yielding at low pressures facilitates plate-like lithospheric behaviour. Results demonstrate that super-Earths are equally likely or more likely than an equivalent Earth-sized planet to be undergoing plate tectonics, and that the low viscosity of PPv has a strong and previously unseen effects on the mantle dynamics of super-Earths.

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1.39
Shear heating and subduction initiation

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Despite its importance in geodynamics, the processes that result in subduction initiation remain incompletely understood. Shear heating has been put forward as a mechanism to create lithospheric-scale shear zones (e.g. Ogawa 1987, Regenauer-Lieb et al. 2001). A scaling analysis highlighted the governing parameters that control shear localization (Kaus and Podladchikov 2006), and showed that the boundary between localization and no localization is quite sharp. Recently, this scaling analysis was extended to include more realistic lithospheric rheologies and structures and it could be demonstrated that shear-heating induced lithospheric scale localization might occur for Earth-like parameters (Crameri and Kaus, 2010).

It is however unclear if all lithospheric-scale shear zones evolve into self-sustaining subduction zones. Here, we therefore extend the models used by Crameri and Kaus to greater depths and take into account an underlying asthenospheric mantle.

Using visco-elasto-plastic numerical models, we show that for certain parameters, lithospheric shear zones evolve into subduction zones when convergence is forced.

![Figure 1: Subduction resulting from forced convergence of two oceanic plates of different age. Colors show composition, white contour lines denote isotherms.](image-url)
1.40

Dislocation glide in experimentally deformed natural quartz single crystals

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Samples of natural milky quartz were deformed in a Griggs deformation apparatus at different confining pressures (700 MPa, 1000 MPa, 1500 MPa), with constant displacement rates of 10⁻⁶ s⁻¹, axial strains of 3 - 19%, and temperatures of 700°C to 1000°C. The single crystal starting material contains a large number of H₂O-rich fluid inclusions. Directly adjacent to the fluid inclusions the crystal is essentially dry (determined by FTIR).

The samples were cored from a narrow zone of constant “milkyness" (i.e. same density of fluid inclusions) in a large single crystal in two different orientations (1) normal to one of the prism planes (⊥m orientation) and (2) 45° to <a> and to <c> (O+ orientation). During attaining of the experimental P and T conditions, numerous fluid inclusions decrepitate by cracking. Rapid crack healing produces regions of very small fluid inclusions (“wet” quartz domains). Only these regions are subsequently deformed by dislocation glide/ dislocation climb, dry quartz domains without cracking and decrepitation of fluid inclusions remain undeformed. Sample strain is not sufficient to cause recrystallization, so that deformation is mainly restricted to dislocation glide. In experiments at lower temperatures there is abundant cracking and semi-brittle deformation, indicating that 800-900°C, represents the lower temperature end of crystal plastic deformation in these single crystals.

Peak strengths (at 900°C) range between 150 and 250 MPa for most samples of both orientations. There is a tentative of decreasing strength with increasing confining pressure, as described by Kronenberg and Tullis (1984) for quartzites, but the large variation in strength due to inhomogeneous sample strain precludes a definite analysis of the strength/pressure dependence in our single crystals.

In the deformed samples, we can distinguish a number of microstructures and inferred different slip systems. In both orientations, deformation lamellae with a high optical relief appear in the usual sub-basal orientation; often they are associated with “fluid inclusions trails”, cracks, or en echelon arrays.

In ⊥m orientation, conjugate misorientation bands sub-parallel to the prism planes can be observed. The misorientation is strongly localized and in some cases extremely high (up to 60° w/r to host c-axis). The deformed-shape of the samples is consistent with prism <a> slip. Unfortunately, as subgrain tilt boundaries in prism <a> slip do not rotate the c-axis orientation, it is expected that a c-axis orientation image does not show misorientation. Nevertheless, changes in the c-axis orientation are observed, indicating the activity of an additional slip system. TEM observations indicate many dislocations with other than pure <a> Burgers vector.

In O+ orientation, we observe the formation of internally kinked shear bands. They are up to 2 mm wide and oriented at α ∼90° w/r to the host c-axis, slightly oblique to the sense of shear. The width of the kinked domains is ∼20-40 µm and their average misorientation is 5°. Individual kink bands, crossing shear zone boundaries, show higher misorientations w/r to the host c-axis (up to 20°). The dispersion of c-axis orientation with synthetic rotation of the c-axis is evidence of basal <a> slip.

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1.41

A new instrumentation to measure seismic waves attenuation

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Attenuation of seismic waves is the general expression describing the loss of energy of an elastic perturbation during its propagation in a medium. As a geophysical method, measuring the attenuation of seismic waves is a key to uncover essential information about fluid saturation of buried rocks.

Attenuation of seismic waves depends on several mechanisms. In the case of saturated rock, fluids play an important role. Seismic waves create zones of overpressure by mobilizing the fluids in the pores of the rock. Starting from Gassmann-Biot theory (Gassman, 1951), several models (e.g. White, 1975; Mavko and Jizba, 1991) have been formulated to describe the energy absorption by flow of fluids.

According to Mavko et al. (1998) for rock with permeability equals or less than 1 D, fluid viscosity between 1 cP and 10 cP and low frequencies seismic wave (< 100 Hz), the most important processes that subtract energy from the seismic waves are squirt flow and patchy saturation. Numerical models like Quintal et al. (2009) calculate how a patchy saturated vertical rock section (25 cm height), after stress steps of several kPa (i.e. 30 kPa) show a dissimilar increase in pore pressure between gas-saturated and liquid-saturated layers.

The Rock Deformation Laboratory at ETH-Zürich has designed and set up a new pressure vessel to measure seismic wave attenuation in rocks at frequencies between 0.1 and 100 Hz and to verify the predicted influence of seismic waves on the pore pressure in patchy saturated rocks. We present this pressure vessel which can reach confining pressures of 25 MPa and holds a 250 mm long and 76 mm diameter sample. Dynamic stress is applied at the top of the rock cylinder by a piezoelectric motor that can generate a stress of several kPa (> 100 KPa) in less than 10 ms. The vessel is equipped with 5 pressure sensors buried within the rock sample, a load cell and a strain sensor to measure axial shortening while the motor generates the seismic waves.

The sensor conditioning system has been designed and realized by us and the acquisition software has been developed in Matlab. We present the first results, at room pressure and temperature, based on the measurements of pore fluid pressure increase in a sandstone sample with a permeability of 200 to 500 mD and partially saturated with water and air.

These preliminary results show the reliability of this new instrumentation to measure seismic wave attenuation at low frequency and to verify the pore fluid flow driven by seismic waves.

REFERENCES

1.42

The effect of deformation on partial melting of metapelitic rock: an experimental study.

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Most of the existing experimental and/or theoretical investigations in the partial melting process emphasized on the role of pressure, temperature and water activity, but did not consider significantly the role of deformation during metamorphism. Natural rocks, however, generally experience phase changes simultaneously with tectonic stress. In this study, we investigated dry, synthetic quartz-muscovite (Fe-rich) system to explore the role of deformation on the reactions kinetics. Torsion experiments were conducted in an internally heated gas medium deformation apparatus at 750°C and at confining pressure of 300 MPa with a constant strain rate of 3x10^-4/s (1 shear strain ~ 1 hour). Static experiments were performed under same P-T conditions as for the deformation ones.

In both static and dynamic experiments the partial melting of muscovite and quartz produces melt + biotite + sillimanite + K-feldspar. The rates of melting and crystallization are independent of imposed conditions (static/dynamic) during the first 1.5 hours of experiments. After this time, deformation takes over and gradually become effective in determining the kinetics. The results indicate that the melt fraction in dynamic experiments is higher than static experiments at the same nominal P-T conditions. It is observed that kinetics of partial melt generation is 1.7 times higher in dynamic conditions compared to static ones. We propose few different explanations for this phenomenon: strain energy, local pressure drop and subsequent melt transportation, overheating because of shear, additional surface energy because of crushing of mineral grains during deformation and effect of viscosity. In this study we attempt a first order assessment of the feasibility of each mechanism.

1.43

Mantle Convection, Stagnant Lids and Plate Tectonics on Super-Earths

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The discovery of extra-solar super-Earths has prompted interest in their possible mantle dynamics and evolution, and in whether their lithospheres are most likely to be undergoing active plate tectonics like on Earth, or be stagnant lids like on Mars and Venus.

The origin of plate tectonics is poorly understood for the Earth, likely involving a complex interplay of rheological, compositional, melting and thermal effects, which makes it impossible to make reliable predictions for other planets. Nevertheless, as a starting point it is common to parameterize the complex processes involved as a simple yield stress that is either constant or has a “Byerlee’s rule” dependence on pressure (e.g., [Tackley, GCubed 2000ab] in 3D cartesian geometry; [van Heck and Tackley, GRL 2008] in 3D spherical geometry).

Because the simplifying assumptions made in developing analytical scalings may not be valid over all parameter ranges, numerical simulations are needed; the one numerical study on super-Earths to date (O’Neill and Lenardic, GRL 2007) finds that plate tectonics is less likely on a larger planet, in apparent contradiction of analytical results.

To try and understand this we here present new calculations of yielding-induced plate tectonics as a function of planet size, focusing on the idealized endmembers of internal heating or basal heating as well as different strength profiles, and compare to analytical scalings.

We conclude that for internally heated convection plate tectonics is equally likely for terrestrial planets of any size. For basally heated convection plate tectonics gets more likely with increasing planet size.
1.44

Dynamics of crustal growth at active continental margins: numerical modeling

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The dynamics of crustal growth under active continental margins were analyzed by using a coupled 2D petrological-thermomechanical numerical model of an oceanic-continental subduction process. This model includes spontaneous slab retreat and bending, dehydration of subducted crust, aqueous fluid transport, partial melting, melt extraction and melt emplacement in form of both extrusive volcanics and intrusive plutons. Depending on variable model parameters such as plate velocities and degree of rheological weakening induced by fluids and melts, the following three geodynamic regimes of crustal growth were identified:

(i) stable subduction without plume development
(ii) subduction associated with plume emplacement
(iii) subduction accomplished by lithosphere extension and back arc spreading.

Crustal growth in a stable subduction setting results in the emplacement of flattened intrusions within the lower crust of mainly basaltic to andesitic composition. At first melts extracted from partially molten rocks located atop the slab (i.e. hydrated mantle, sediments and basalts) intrude into the lower crust followed by mantle-derived (wet peridotite) basaltic melts from the mantle wedge. Thus, extending plutons form associated with low crustal growth rates (15 km³/km/Myrs) and a successively increasing mantle component.

In a plume-present regime, crustal growth is accomplished by the formation and emplacement of silicic plumes. In the course of subduction localization and partial melting of basalts and sediments along the slab induces Rayleigh Taylor instabilities. Hence, buoyant silicic plumes are formed, composed of partially molten sediments, basalts (oceanic crust) and serpentine. Subsequently, these plumes ascend, crosscutting the lithosphere before they finally crystallize within the upper crust in form of silicic batholiths. Additionally, basaltic intrusions within the lower crust are formed derived by partial melting of rocks located atop the slab and inside the plume.

Crustal growth rates increase with time before reaching a steady state (60km³/km/Myrs). The mantle component of the newly produced crust decreases with time. Subduction in an extensional arc setting results in decompression melting of dry peridotite. The backward motion of the subduction zone relative to the motion of the plate leads to thinning of the overriding plate. Thus, hot and dry asthenosphere rises into the neck as the slab retreats, triggering decompression melting of dry peridotite. As a result crustal growth rates increase to values of about 100km³/km/Myrs.

1.45

Evidence of Permian HT metamorphism in Austroalpine units of the Internal Western Alps?

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The Internal Western Alps comprise predominantly continental terranes that were assembled during the oblique Alpine convergence of S-Europe and the thinned Apulian margin. Terranes derived from Apulia are termed Austroalpine units; these are well exposed in the Sesia Zone, the Dent Blanche nappe, and a few smaller tectonic outliers. Basement rocks are dominant in all of these units, but Permian intrusive masses are widespread, and thin trails of post-Variscan sediments have locally been recognized. Despite the HP/LT Alpine overprint (blueschist to eclogite facies) of all units, relics of an earlier HT metamorphic history are abundant. The Alpine HP-imprint is most distinctly developed in mylonites, both wi-
thin the various terranes and along contacts to adjacent ones; pre-Alpine HT assemblages are commonly preserved in less deformed rocks.

The present study focussed on samples from shear-zones with clear evidence of the Alpine HP metamorphism. To date specific metamorphic stages, detailed microstructural and petrologic analysis of select samples was followed by in-situ U-Th-Pb dating of allanite, titanite, and zircon. Much to our surprise, most ages do not reflect the Alpine HP-stage, even though robust U-Th-Pb chronometers were employed. Predominant are Permian ages. Examples presented here are chosen to document striking similarities, from SW-Sesia to the Dent Blanche, i.e. across the well established Austroalpine HP-units.

(1) SW Sesia zone (II DK unit: 'seconda zona dorio-linzigitiaca', Apulian lower crust)
- Locality Vasario (Valle di Ribordone): Across a m-scale shear zone within the II DK unit (metabasics with thin slices of intermediate rocks), blueschist-facies assemblages are best developed in the core of the shear zone; glauc + pheng + clz define the mylonitic foliation. Zircon grains in the mylonites of intermediate composition show igneous cores with sector-zoned metamorphic overgrowths. Such rims are typical of granulate-facies; LA-ICP-MS data reveal a Permian age (275 Ma).
- Locality Pasturera (Val Soana): A shear zone developed along the northern contact of II DK to Gneiss Minutti in the SW Sesia zone. Strongly deformed parts near the contact show a greeenschist-facies (ep + ab + chl) overprint. However, the less deformed margins of the shear zone retain blueschist-facies assemblages (glauc + pheng) with large euohedral allanite. Preliminary LA-ICP-MS data for allanite from the blueschist-facies sample yield ages of 280-330 Ma.

(2) Dent Blanche nappe
- Locality N of Lago Cignana (Valtournanche): Tightly folded metacherts and carbonates contain blueschist facies assemblages (rieb-grt-qtz-ep). SHRIMP data from titanite in siliceous marbles and allanite in metacherts yield reproducible age data in three groups: 160-190 Ma, 270-290 Ma, and 300-350 Ma. The younger ages are thought to reflect heating associated with the Jurassic rifting that preceded the Alpine collision; the oldest ages represent Hercynian relics, but again there are Permian growth zones. Garnet in impure metacherts contain metamorphic allanite inclusions dated at 290 Ma as well.

(3) Dent Blanche nappe (polymetamorphic Valpelline basement)
- Locality Thoules (Valpelline): granulitic-facies assemblages are well developed in paragneisses (grt-sil-bt-pl-qtz)
EMP geochronological data for monazite from the granulitic sample yield preliminary ages of 220-260 Ma.

While a definitive interpretation of these isolated age data is surely premature, the consistency of the data from several settings is remarkable and demands a discussion in the regional framework. Permian magmatism is of course well established in many parts of the Alps, with mafic intrusives (mostly gabbros) and more evolved types (e.g. Mucrone granodiorite, Arolla granite) occurring in the internal Western Alps. However, the widespread and diverse settings of the present observations is unlikely to represent contact-metamorphic phenomena. Regional metamorphism in the Permian is now well established in the Eastern Alps (Schuster and Stüwe, 2008). In the Western Alps, there is only sparse evidence for Permian metamorphism (e.g. Rebay and Spalla, 2001), quite possibly because Variscan rocks in the corresponding Austroalpine units are generally of upper amphibolite facies to migmatic grade, rendering difficult the recognition of a subsequent Permian phase. Certainly the model of Permian rifting producing a high heat-flow regime that caused large-scale magmatic underplating and HPHT-metamorphism, as advocated by Schuster and Stüwe (2008), deserved further attention and scrutiny in the Western Alps.

The present communication comes out of our comprehensive effort aimed at documenting the Alpine PTDT-history in the Internal Western Alps. Why then do the shear zones we investigated, which were chosen for their clearly identifiable HP assemblages, retain the pre-Alpine chronometers so well? An obvious possibility is that these shear zones were set up during pre-Alpine tectonic activity (Jurassic rifting, Permian or Variscan or even older orogenies) and reactivated during late-Cretaceous and early Tertiary Alpine convergence.

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1.46

Structural evolution of the Zagros fold-thrust-belt: insights from the U-Th/He thermochronometry (Ap. and Zr.)

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The Zagros Fold-Thrust Belt (ZFTB) is located south of the Arabian-Eurasian plates’ suture.

Deformation and uplift in the ZFTB have been triggered by collision at about 35 Ma. However, the timing of the deformation since 35 Ma is debated because it is, up to now, ill-constrained by quantitative methods.

Combining structural analysis and low temperature thermochronology (AHe and ZHe) helps to constrain vertical movements related to the building of this orogen.

The samples come from Cambrian sandstones, Paleogene Flysh and Neogene Molasse. In this study, AHe ages are used to quantify the burial history of the Paleogene flysh and Neogene molasse basins, and interpret the kinematic evolution of the ZFTB. With ZHe ages, it is possible to estimate the thickness of the total Phanerozoic sedimentary pile.

AHe and ZHe ages on detrital samples are presented on two regional cross-sections at crustal scale of the Lurestan and the Kuhzestan regions (Fig. 1).

The only available AHe and ZHe ages have been provided by Gavillot et al. (2010) in the Kuhzestan along the main thrusts, in salt plugs and in the syn-collisional conglomerate Fm.

In Lurestan, the samples of the base of the Neogene molasse show partially reset (~75°C) AHe ages, which indicates 2-3 km of burial for this formation and a thinning toward the interland.

Paleogene flysh AHe ages are also partially reset which is interpreted as a minimum burial of 2-3 km in the central Lurestan. Toward the north, completely reset ages suggest a thickening of this formation toward the interland.

Finally, AHe ages lead to propose that exhumation linked to the last compressional deformation stage occurred after 12 Ma along the suture and in the most internal parts of the Fold-Thrust Belt, and subsequently propagated toward the foreland, with exhumation younger than 2-3 Ma in the frontal folds.

In Kuhzestan, partial reset of ZHe ages (200-160°C) at the base of the Cambrian Fms. is evidence for a maximum burial of 7-9 km. Whereas near the top, ZHe ages at 350 Ma, not affected by the subsequent Phanerozoic sedimentary pile, allow questioning about the meaning of this signal commonly mentioned in different studies all around the Arabian plate (e.g. Kohn et al., 1992).

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Figure 1: Cross-sections of the Lurestan (upper section) and south Kuhzestan (lower section). Thermochronological ages (AHe and ZHe) are located (white and black rectangles respectively). Triangles above the section indicate minimum age for exhumation in each structural domain. MZF: Main Zagros Fault, HZF: High Zagros Fault, MFF: Main Frontal Fault (or Flexure), KSF: Kuh-e Sefid Fault, SSZ: Sanandaj-Sirjan Zone, KCZ: Kermanshah Cruch Zone, HZ: High Zagros, IZ: Izeh Zone, DE: Dezful embayment.