Extensional fault patterns of the Lepontine Dome  
(Central Alps, Switzerland)  
deduced from paleostress inversions and morphotectonics

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The main updoming of the Lepontine Gneiss dome started some 32-30 Ma ago with the intrusion of the Bergell tonalites and granodiorites, concomitant with dextral strike-slip movements along the Tonale and Canavese Lines (Argand’s Insubric phase). Subsequently, the center of the main updoming has migrated slowly to the west, reaching the Simplon region some 20 Ma ago. The architecture of this Oligocene-Miocene basement unit, resulting from ductile and semi-ductile deformations, is composed by two “sub-domes”: the Simplon dome to the west and the Ticino dome to the east, separated by the “Maggia steep zone”. Both of them are formed mainly by stacking of different nappes consisting of orthogneissic cores discontinuously mantled by a schistose paragneissic envelope and overlying Mesozoic metasediments which are tectonically interposed between the older sequences and interpreted as “nappe separators”. These ductile and semi-ductile structures begin to be well documented (Steck and Hunziker, 1994) and imaged (Maxelon and Mancktelow, 2005) contrary to the brittle post-nappe tectonics of the dome that still remains under-explored.

Thus, the network of faults and morphotectonic lineaments of the western parts of the Lepontine dome (Central Alps) is here examined to investigate the late alpine kinematics from Oligocene to Quaternary times. Calculations of the stress distributions (P-T-B axes method, numerical dynamical analysis, direct inversion methods, dihedral calculations) have yielded a stress field which may be attributed to an important phase of extension during Oligocene to Miocene, probably following the early “core complex” stage of extension leading to the development of the Lepontine gneissic dome. Indeed, all the methods indicate that this crustal-scale rigid block faulting is characterised by a normal paleostress tensor with a NE-SW trending axis _3 (similar to those calculated all along the Simplon line). Nevertheless, it appears different sets of faults, well expressed by morphological features visible on the satellite images. Different sets of fault can be observed with the following trend: NW-SE with normal offset (the most represented), N90° to N100° with normal/dextral offset, and N0° to N20° with normal/sinistral offset. This particular fault pattern seems concordant to transtensional models established previously (Schreurs and Colletta, 1998; Waldron, 2005), where incremental strain associated with simple-shear deformation in a strike slip zone could explain the small variations of fault trend.

The occurrences, characteristic for a specific fault set, of cohesive or non-cohesive cataclasites derived from gneisses associated with pseudotachylite veins, fault planes with chlorite and quartz slickenslides, and/or gouge, suggest an important brittle history and, especially, probably a progressive evolution in the formation of these different sets of fault, sometimes involving reactivation of some of them.

These field-based studies are complemented by on-going analytical work on pseudotachylites in order to better constrain the timing of the deformation. Indeed, some occurrences of true glass, resulting from melting/quenching processes, would allow timing constraints to be obtained. Some morphological features suggest also a possible quaternary activity of some WSW-ENE trending fault.

This late orogenic extensional tectonic evolution of metamorphic nappe stacks appears well in line with others studies on the entire alpine arc from the Bergell intrusion (Ciancaleoni, 1999) to the western boundary (Sue et al, 2005).
Figure 1. Examples of late brittle extensional structures.

a) Post mylonitic fault near Val Calnegia. Mylonitic foliation, dipping at ca. 20° to the NW is cut by a later set of conjugate brittle normal faults, representing a graben-like structure, in biotite/muscovite gneiss of the Antigorio unit.

b) Close up of outcrop shown in a). Feldspar clasts as well as asymmetrically sheared quartz veins indicate a normal “top to the NE” shear sense.

c) Close up of outcrop shown in b). A steep normal fault plane mineralized with quartz and chlorite, of which striations indicate a normal sense of shear.

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HP-rocks in the Alps: Review of isotopic ages based on petrology and their geodynamic consequences

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To understand the spatial and temporal evolution of collisional orogens, such as the Alps, age data on the timing of subduction/extrusion of individual units may set important markers. Regrettably, the interpretation of age data is rarely unambiguous, and this limits their value despite their high precision. On compiling isotopic ages and petrological information for the main oceanic and mélangé units in the Western and Central Alps, this difficulty translates to substantial uncertainty in the geodynamic scenarios.

Individual isotopic mineral ages from high pressure (HP) metamorphic samples are interpreted as either (1) early metamorphic growth on a prograde path, (2) strong metamorphic/deformational overprint, (3) diffusional resetting of the chronometer, or (4) uncertain due to currently limited understanding of the mineral chronometer.

Where data on the PT-evolution are lacking, individual age data do not easily translate to constraints for the geodynamic setting in a given geological period. It is commonly assumed that (2) reflects conditions near “peak metamorphism” (T_max?). However, unless based on robust thermobarometry, this interpretation is generally at odds with current understanding of petrologic evolution. For some published data sets of HP-ages in the Alps, there is insufficient petrological evidence to discern between (1) and (2), and (4). For most of the relevant data sets (3) is of minor concern.

Available age data do provide some markers on the subduction history. We connect some Zir U/Pb and Lu/Hf data in eclogites of the Sesia zone with the timing of HP-equilibration at 65 Ma (Duchêne et al. 1997, Rubatto et al., 1999). For the Zermatt unit, Sm/Nd and Lu/Hf data indicate prograde garnet growth at around 40 Ma (Lapen et al., 2003). The interpretation of the subductional evolution for the western Alps is directly linked to the location the Sesia unit. This unit is seen as a continental fragment inside the Piemont-Liguria ocean. If so, the age of HP-metamorphism in the Sesia unit sets a lower limit for the subduction age of this paleogeographic unit. Provided the Sesia unit was subducted in sequence with subsequent parts of the preserved Piemont-Liguria ocean, the western Alps underwent subduction from late Cretaceous (Sesia unit) to Eocene (Zermatt unit). This implies a time interval for subduction along this plate boundary is ~25 Ma, which translates to an average subduction rate of 1.6 cm/a for the size (400 km) of this paleogeographic unit. This rate is consistent with published plate-motion data for the Alps at this time.

The same paleogeographic unit (i.e. Piemont-Liguria-ocean) is represented by the Platta-Forno-Malenco units in Eastern Switzerland and Italy. These units are incorporated in the Apulia realm in the Cretaceous (110-90 Ma; Villa et al. 2000), no HP-metamorphism has been documented from these units. The tectonics related to the Platta unit is a nappe-like incorporation during west directed thrusting. The timing and the tectonic processes are different in the Platta and the Zermatt units. This indicates that some pieces of the Piemont-Liguria ocean were obducted early in their history during west vergent thrusting, whereas the main portion was subsequently subducted, during the lower Tertiary.

Isotope age data from the Central Alps indicate high-pressure relics in a mélange zone, with HP-phases forming in different location within an extended time interval of 65-37 Ma (Brouwer et al. 2005, Gebauer 1999). The timing is thus roughly consistent with age data of HP-events in the western Alps. However, it is clear from field relations and documented PT-paths that individual fragments in the mélange units, as well as tectonic slivers distributed along various nappe contacts evolved along
largely independent paths during the collisional assembly of the Central Alpine accretion channel (Engi et al., 2001).

Briançonnais units initially located north and northwest of the Piemont-Liguria-ocean indicate a large variety of HP-ages: 52-46 Ma for Monte Rosa (Lapen et al. 2004); 43 Ma for Gran Paradiso (Mefhan-Main et al. 2004); 38-33 Ma for Dora Maira (e.g. Rubatto & Hermann 2001, Dühene et al. 1997). These ages largely overlap with data for Piemont-Liguria and mélange units in the Central Alps, in contrast to the different initial paleogeographic position. There is no obvious data set to constrain the evolution in the subduction direction. As shown by Lapen et al. (2003), the PTt-evolution for certain small units can be reconstructed, but these data are insufficient to understand the subduction history at a plate-tectonic scale. In order to differentiate between former paleogeographic units, the resolution of isotopic dating and the understanding of the chronometers themselves must be improved. The occurrence of large scale variations, with different behaviour during subduction and extrusion (such as the Sesia unit), offers the possibility to improve reconstructions of the geodynamic history.

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How do uplift, sedimentation and erosion interact in the Alpine evolving orogen from Eocene to Present? – Analogue modelling insights

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The evolution of the Alpine orogen is largely governed by the kinematics of thrust and fold development. The internal dynamics of the mountain belt is well established and documented. Recently, studies have focused on the influence of surface processes on the dynamics of the orogenic wedge and the evolution of topography. To better constrain the role of erosion and deposition on the Alpine morphology and their interaction with lithospheric-scale processes such as tectonics, we performed a series of analogue modeling experiments. Our aim is to analyze tectonic processes and foreland molasse basin evolution developed in the northern part of the orogen in response to the Alpine compression (from Eocene to Present), under given conditions of erosion/sedimentation. Our set-up is based on a retro-deformed section of the western Alps by Burkhard & Sommaruga (1998) that extends from the Penninic Nappes (South-East) to the Jura fold-and-thrust belt (North-West).

Successive models have been tested to constrain the geometry of the different tectonic units /depositional realms. We have simplified the orogenic lid to a homogeneous unit representing mainly the Penninic. It overrides basement and cover units considered to be the equivalent of the European margin; from south to north: Ultrahelvetics, Helvetics, Autochthonous and Jura, including the associated basement massifs. The different present units in the basic setup are simulated by analogue materials (sand and silica powder) chosen for their rheological contrasts. For instances, the basement units are formed by a very cohesive mix of silica powder and sand. In contrast, the more “deformable” and easily erodable cover units are composed of sand only. Glass bead layers are employed as décollement levels in the series: Triassic layers at the base of the Mesozoic cover and the base of the first marine molasse deposits (UMM). They are also used to model the inherited normal faults bordering the basement units and currently playing as reverse faults.

In the following we present and discuss results and insights obtained from one experiment only among the 15 performed. In this experiment the Penninic overrides the European basement and cover units in an initial stage of the orogen corresponding to the closure of the alpine oceanic domain with no erosion/sedimentation. Then the orogen becomes aerial and we erode material to maintain the original slope of the wedge and we regularly deposit “molasse sediments” in the foreland.

We observe a continuous and important internal deformation of the Penninic lid due to retrothrusting [Fig.1] and a piggy-back basin appears rapidly at its passive front. While the different décollement levels are successively activated (for instance the décollement of the Helvetic nappes is particularly visible), they then continue to act all together. Thus, the formation of the orogen seems to be a continuous phenomenon and not a succession of events, as proposed by some authors. A major structural development during the experiment is the formation of the basement nappes stack [Fig.1]. The combined effect of tectonics and erosion leads to localization of the exhumation on basement units (Mont-Blanc, Alguilles Rouges and “Infra-Rouges” massifs) and a part of the autochthonous European foreland basement is underplated spontaneously as a succession of slices. Mesozoic cover is trapped in the nappe stack formed by the basement units that become vertical backward and extremely sheared. Only due to erosion and tectonics, the front of the Penninic lid is isolated because of the basement units’ uplift and it constitutes the Préalpes klippen [Fig.1]. Another very interesting fact in our experiment is that the Jura development [Fig.1] roots in a unique décollement level through the basement. Final volumes of eroded and sedimented material in the experiment...
are in a good agreement with the percent proposed for the Alps since they constitute almost 15% of the Penninic eroded material. Furthermore, syndeformational erosion makes it possible that important volumes of material are eroded out of the geological record. This bears important consequences on possible restorations of cross sections, which would underestimate original lengths and total Alpine shortening.

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Figure 1. Principal structural developments during the analogue modelling experiment
Granitic rocks initially have a bulk homogeneous and isotropic texture and represent good analogues for the study of the rheological behavior of the continental crust. When deformation occurs, these granitic rocks commonly undergo heterogeneous strain reflected by patterns of anastomozing shear-zones. These shear-zones surround lens-shaped domains of weakly deformed rocks (e.g. Ramsay & Allison, 1979; Choukroune and Gapais, 1983). The shear zone patterns are described as slip surfaces that accommodate most of the bulk deformation. Therefore they have been used as reliable and large scale shear criteria and strain markers (e.g. Gapais et al., 1987).

This study is integrated in a wide thematic project focused on the use of shear zone patterns in metagranites to understand the deformation and kinematics in different tectonic units along the N-S NFP20-East profile of the Alps. On this profile, the metagranite deformation is used as a strain and kinematic indicator in the External Crystalline Massifs (ECM, Aar massif, Choukroune and Gapais, 1983; Gotthard massif, Marquer, 1990), in the Upper Penninic nappes (Tambo nappe, Marquer, 1991; Suretta nappe, Marquer et al., 1996), in the late alpine intrusions (Bergell intrusion, Ciancaleoni et al., submitted; Novate granite, Ciancaleoni and Marquer, submitted; Sondrio Intrusion, this study). Furthermore, geochronological studies supported by a careful structural and microstructural control from shear zones yield inferences about the age for the Alpine deformation events (e.g. Challandes et al., 2003). In the different intrusions, the symmetrical/asymmetrical patterns versus schistosity, lineation and P-T strain axes are used as large-scale kinematic indicators and discussed in terms of coaxiality/non-coaxiality of the deformation.

The Truzzo and Roffna metagranites of the Tambo and Suretta nappes, respectively, have undergone a finite heterogeneous strain under HP-LT to medium and low-grade metamorphic conditions during the Alpine deformation, respectively (Marquer, 1991 and references therein; Marquer et al., 1996 and references therein). The shear zone patterns in both granites reveal the non-coaxial kinematics of the main deformation phases, associated with a NNW thrusting during the Briançonnais accretionary prism stacking in the time span 50-45 Ma (e.g. Challandes et al., 2003) and subsequent (40-35 Ma old, Challandes et al., 2003) east-directed thinning of the nappe pile, coeval with the progressive activity of the Valaisan and lower Pennine thrusting towards the external parts of the Alpine belt.

Closer to the Insbruc line, the fault kinematic analysis of the conjugate shear zone patterns in the Sondrio intrusion and Novate granite indicate a coaxial/non-coaxial deformation, respectively, associated with dextral backthrusting on the Insbruc mylonites at 30-32 Ma and orogen-parallel extension at 25 Ma (Ciancaleoni and Marquer, submitted) along the brittle-ductile Forcola mylonites (Meyre et al., 1998). In the Bergell intrusion the late faults and shear zones formed under brittle-ductile conditions is distributed in space and time into extensional and transcurrent displacements, leading to lateral extrusion of the Eastern Central Alps by the late Oligocene onwards (Ciancaleoni et al., submitted).

The ECM are exposed in the External Alps of Switzerland and belong to the European plate involved in the Tertiary Alpine continent-continent collision and are thrusted towards the northwest under greenschist facies (Aar massif) to amphibolite facies (Gothard massif) conditions (e.g. Pfiffner et al.,

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**The spatial extent and characteristics of block fields in Alpine areas: evaluation of aerial photography, LIDAR and SAR as data sources**

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The Alpine schistosity and shear zone patterns in the core of the ECM is interpreted as a bulk coaxial NW-SE shortening associated with a vertical stretching during the underthrusting of the ECM (e.g. Marquer, 1990). In the Aar shear zones, the Ar-Ar syn-kinematic mica dates have been interpreted as ductile deformation ages around 23-16 Ma (Challandes, 2001).

Shear zone patterns study in metagranites is an important tool to filter Alpine/pre-Alpine deformation and to interpret the bulk alpine kinematics at large scale in different tectonic units. These studies also bring new knowledge about the mechanical behaviour of the continental crust, which is mainly controlled by heterogeneous deformation at different stages of the mountain building processes (subduction/collision). Furthermore heterogeneous deformations recorded in basement rocks and metagranites leads to preserved lense-shaped domains where relics of prealpine can be carefully investigated.

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Continuous local GPS network for the assessment of small scale Alpine geodynamics

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The objective of project TECVAL is to detect and assess tectonic movements in the canton Valais by modern geodetic techniques and correlate them with seismic activity in view of seismic hazard assessment. The canton Valais is one of the seismically most active regions in Switzerland as shown by historical records and seismic compilations. In this region 4 large earthquakes occurred in the past 250 years reaching moment magnitudes of about 6. The largest earthquake of the 20th century in Switzerland took place in the area between Ayent and Sierre, Valais. This event damaged 3485 buildings in the Valais and the surrounding cantons and caused 4 fatalities.

Levelling data in Switzerland collected for more than 100 years revealed an ongoing uplift of the Alps. This uplift reaches a maximum of 1.3 mm/a in the canton Valais relative to the Swiss molasse basin. Yet there is no geodetic data which describe horizontal tectonic movements in the study area. Project TECVAL aims at removing this short-coming by installing a permanent GPS network consisting of six stations. The layout of this new GPS network focuses on a conspicuous seismic belt north of the Rhône valley extending from the Wildstrubel area to the Haute-Savoie, France.

The detection of pre-, co- and post-seismic slips and the determination of the faulting style by geodetic techniques within this seismic belt are of particular interest. The eastern part of the seismic belt is parallel to the Sion-Courmayeur zone separating two tectonic provinces. The Helvetic and the Penninic nappes differ seismically in the style of faulting. The former is dominated by strike-slip faulting whereas the latter is characterized by normal faulting.

GPS measurements of the new network, the Automated GPS network operated by Swisstopo (AGNES) and GPS campaigns will be analyzed and combined with existing high-precision levelling-data resulting in a new kinematic field of the earth’s crust in the Valais. Seismic data compiled by the seismological service (SED) will be utilized to form a coherent kinematic deformation model from which strain and stress parameters will be deduced.

The extremely small deformation rates expected necessitate sophisticated error analysis and detection methods. The concepts will be presented and demonstrated for selected GPS time series.
Eocene to Early Oligocene syn-rift deposits of the southern Upper Rhine Graben (URG) accumulated under a restricted environment. Sedimentation was controlled by local clastic supply from the graben flanks, as well as by strong intra-basinal variations in accommodation space due to differential tectonic subsidence, that in turn led to pronounced lateral variations of the depositional environment.

Three large-scale cycles of intense evaporite sedimentation were interrupted by temporary changes towards brackish or freshwater conditions. They form three major base level cycles that can be traced throughout the basin, each of them representing a stratigraphic sub-unit.

A relatively constant amount of horizontal extension (DL) in the range of 4 to 6 km has been calculated for the URG from numerous cross sections. The width of the rift (Lf) varies between 30 and almost 60 km, resulting in a variable upper crustal stretching factor b along the graben. Apart from block tilting, tectonic subsidence was therefore largely controlled by changes in the rift width (Lf). The along-strike variations of DL are responsible for the development of a deep, trough-like evaporite basin (Potash Basin) in the narrowest part of the southern URG, adjacent to shallow areas in the wider parts of the rift such as the Colmar Swell in the north and the Rhine Bresse Transfer Zone in the south that also forms a major swell within the graben.

Under a constant amount of extension, the along-strike variation in rift width is the principal factor controlling depocenter development in extensional basins.

Figure 1. Digital elevation map of the study area superimposed by a simplified fault grid and isopachs of graben fill (broken lines; thickness in m). The southern part of the graben was strongly uplifted and exposed during the Neogene. The area forms an intra-continental high, gathering the watersheds between North Sea, Black Sea and the Mediterranean.
Phase relations and prograde evolution of LREE-bearing silicate-phosphate assemblages in low-grade metapelites: consequences for U-Th-Pb geochronometry in the Central Alps

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Geochronological data impose essential anchors on the thermal and tectonic evolution of orogens such as the Alps, provided the age data can be properly interpreted. This proves more difficult for low-grade metamorphic rocks than for igneous or amphibolite facies rocks. For samples from the northern Lepontine Alps (e.g. Lucomagno area), ages reported range from <13 Ma to >350 Ma (Hunziker et al., 1992), and the significance of many discrepant results remains controversial.

Among the successfully used radiometric techniques, those involving the U-Th-Pb isotopic systems are among the most powerful. A variety of chemically robust minerals such as monazite, zircon, xenotime, and titanite yields high-precision ages. Since phase relations for these phases and several other, potentially useful LREE-minerals are poorly known at low-grade metamorphic conditions, comparable age data are so far difficult to obtain and interpret for (sub)greenschist facies rocks. In this study we explore the potential of REE-bearing minerals as U-Th-Pb geochronometers in Al-rich metapelites.

The classic Lucomagno-profile of metapelites and -marls studied by the late Prof. Martin Frey contains promising samples (collection at the University of Basel), for which petrographic data exist. We have further investigated these and other samples, notably of the Triassic Quartenschiefer formation. Samples representing prograde conditions between anchizonal and lower amphibolite facies grade were taken along the well constrained metamorphic field gradient between the Helvetic pre-Alps and the northern parts of the Lepontine Dome. The strategy developed has been to characterize (by ß-scanner, SEM, and EMP) the REE-bearing minerals texturally and chemically at the micrometer scale.

In diagenetic to low-grade metamorphic rocks, LREE are incorporated in monazite; this mineral occurs variably as minute grains (<5 μm, present in most samples), roundish and/or irregular grains (~50 μm, mostly in low-grade rocks) but also as grains with textural evidence of recrystallisation (~50 μm, near the “chloritoid-in” zone boundary). With the appearance of chloritoid, monazite vanishes, and REEs are taken up in homogeneous, idiomorphic allanite (10-30 µm) found in intergranular positions or as inclusions in chloritoid. With increasing metamorphic grade, up to the “chloritoid-out” zone boundary, allanite grains increase in size (up to 500 µm) and very commonly acquire a rim of epidote. Very local replacement of allanite grains, with monazite and REE-carbonate occurring at their periphery, has been observed in samples showing evidence of faint late-stage hydrothermal alteration. In higher-grade metamorphic rocks (St-Ky-Gt-Bt assemblage), allanite in part is texturally replaced by monazite-xenotime, which are associated with biotite, staurolite or plagioclase. In these samples, monazite has not been found as inclusions in garnet. In all of the samples studied, HREE have been observed to be mainly incorporated by xenotime. Its origin is considered to be mainly diagenetic but, since it grew in association with monazite replacing allanite, a metamorphic mineral reaction can be inferred as well.

The habit of newly formed monazite in very low grade metamorphic rocks suggests that this mineral may record diagenetic and/or low grade metamorphic growth. Monazite and xenotime in replacement textures from allanite appear as good
candidates to obtain reliable P-T-t conditions of the highest grade metamorphic rocks investigated. In addition, U-Th-Pb dating of chemically homogeneous allanite offers attractive opportunities, since this mineral is widespread from its appearance in the chloritoid zone to its breakdown in the lower amphibolite facies (northernmost parts of the Lepontine domain). However, to obtain interpretable age data, care must be taken to avoid even minor hydrothermal effects on allanite.

Our efforts to extend usable U-Th-Pb chronometers and to relate the new age data to P-T conditions of specific mineral reactions for external parts of the Central Alps complement the ongoing Ar-Ar study by Allaz et al. (2004). By combining geochronological data based on different isotopic systems for the same sequence of metamorphic samples, we expect to improve both the temporal constraints for the tectonic and thermal history of the Alps, as well as the basis to interpret discrepancies amongst such age data elsewhere.

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Early Carboniferous age of the Versoyen magmatism and consequences: non-existence of a “Valais ocean” in the Western Alps


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Mafic magmatic rocks occur at several places in the Lower Penninic nappes of the Alps. They are generally ascribed to oceanic crust of a so-called “Valais ocean” of Cretaceous age which plays a fundamental role in several modern models of Alpine paleogeography and geodynamics.

In fact they are quite discontinuous and their age and tectonic position are in most cases very uncertain. The type locality for the definition of the “Valais ocean” is the Versoyen, on the French-Italian boundary west of the Petit-St-Bernard col. The idea of a “Valais ocean” is based on the following assumptions: (1) the Versoyen series (black schists intercalated with abundant metabasalts) is the overturned stratigraphic base of the underlying Cretaceous-Tertiary (?) Valais-Tarentaise series; and (2) it has a Cretaceous age. We present new field and geochronological data that severely challenge both assumptions.

A) Field data: Detailed mapping and stratigraphic/structural analyses reveal that: (1) The contact of the Versoyen over the Valais-Tarentaise series is tectonic and not stratigraphic. (2) The contact of the Triassic-Jurassic Petit-St-Bernard (PSB) series over the Versoyen is stratigraphic and not tectonic (as believed by all authors since 50 years). This is demonstrated by its erosive nature, by small sedimentary dykes of PSB calcschists penetrating into the Versoyen black schists, and by the reworking of fine-grained detrital Versoyen material into the basal PSB calcschists. (3) The Versoyen series also shares more phases of deformation and metamorphism with the PSB than with the Valais-Tarentaise series. We conclude that the Versoyen series is the basement of the PSB, and therefore has a Paleozoic age.

B) Geochronological data: The main gabbroic body intruded into the Versoyen series has been sampled at three places. All three samples provided zircons that have been dated with the SHRIMP II ion microprobe at the Center of Isotopic Research (VSEGEI) at St Petersburg. The results are identical for the three samples: (1) In comagmatic zircons all analytical data are well grouped on or very near the Concordia curve and give a crystallization age of 337.0 ± 4.1 Ma (Visean, Early Carboniferous). These zircons show typical oscillatory zoning and no overgrowths or corrosion, and are interpreted to date the Versoyen magmatism. (2) Inherited zircons (e.g. cores) yield ages scattered between about 450 and 700 Ma. (3) The outer rims of a few zircons give younger ages down to about 300 Ma, that we ascribe to a slight lead loss during metamorphism. These geochronological results are in excellent agreement with the field observations.

The Versoyen mafic rocks disappear toward the NE but the “Valais ocean” is supposed to reappear 100 km farther in the Visp-Simplon area where metabasalts and serpentinites are abundant in the Lower Penninic. Our work in this area is still in progress but first results indicate a Paleozoic age of these oceanic rocks is more likely.

**CONCLUSIONS**

(1) The existence of a “Valais ocean” in the Western Alps is highly improbable.

(2) Our results suggest the existence of a Versoyen-Visp ocean of Early Carboniferous age, which could be a back-arc or a pull-apart basin, or a combination of both.

Several major features of Alpine geology will have to be reconsidered, particularly concerning the history of oceans and the correlations with the Graubünden over the Simplon-Ticino dome. We will develop some geodynamical consequences of these facts.
In search of post-glacial active faulting in the western Swiss Alps: results from three-dimensional GPR surveying and paleoseismic trenching

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We have conducted a 3-D ground penetrating radar (GPR) survey (~ 60 x 30 m) across the projection of a lineament of tectonic origin within a small alpine sedimentary basin in the western Swiss Alps. A trenching study was proposed within the basin to look for evidence of post-glacial fault movement.

Paleoseismic excavations in high alpine regions are expensive and time consuming in the absence of heavy earth moving equipment. In addition, the adverse environmental impacts limit the size of any excavation. A non-invasive GPR survey was undertaken to provide a priori knowledge of the subsurface structure, allowing us to locate a single trench that would contribute maximum information to the paleoseismic record.

Conventional 2-D GPR surveys can elucidate structures to a resolution of a few tens of centimetres, but in mountainous regions where subsurface structures are far from simple, the resulting cross sections may be contaminated with out-of-plane reflections of unknown origin, increasing the potential for a false interpretation. We opted to use a 3-D GPR system to reveal the variable thickness of the sediments within the basin and to look for disrupted sedimentary horizons indicative of recent faulting.

GPR data were acquired on a dense grid (18 x 18 cm) using a semi-automated GPR acquisition system comprising a conventional GPR unit coupled with a self-tracking laser theodolite (Lehman and Green, 1999). The data were migrated and depth corrected so that reflections could be interpreted in terms of space rather than time. Cross-sections and depth slices extracted from the migrated data volume reveal two distinct reflection facies resulting from the finely layered sediments and karstic limestone basement (Figure 1). The layered sediments have a maximum thickness of 3.0 m and reflections from the limestone basement can be observed to at least 4.5m depth.

Layering within the sediments appears to be continuous in cross-section without any notable vertical offset attributable to recent faulting. A subtle linear feature with a N-S trend is detected on several depth slices, suggesting a possible fault strand oblique to the projected location of the lineament. To look for signs of deformation within the sediments, we excavated a trench across this linear feature near the middle of the survey area (figure 1). This location was also favourable, because the depth to basement is no greater than 2.2m, thus enabling us to dig a relatively shallow trench and scour the limestone basement for evidence of active faulting.

We present the processed GPR data together with the results of the trenching survey in an attempt to reconcile observations from both techniques.

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Figure 1. A depth slice extracted from the 3-D GPR volume at 1.5m. The finely layered sediments (outlined in white) have a distinct reflection pattern relative to the surrounding karstic limestone. A subtle N-S trending lineation (between the white arrows) is detected in the middle of the survey area. The excavated trench (black box) crosses this lineation and is oriented perpendicular to the projection of the main post-glacial lineament.
Growth mechanism of snowball garnets from the Lukmanier Pass; Central Alps

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Snowball garnets are frequently found in regional metamorphic rocks. A controversy exists on how to account for the development of such microstructures. Most of the time snowball garnets are interpreted as the result of simultaneous growth and rotation of the crystals during syn-metamorphic deformation. In contrast, another school of thought rather suggests that spiral-shape garnets are the result of the rotation of the foliation with respect to the garnet. In this case, the mechanism involves the overgrowth of successive generations of orthogonal foliations. In this study, we re-examine this issue and propose an alternative way to explain the formation of snowball garnet porphyroblasts by combining different and independent methods of investigations.

The snowball garnet samples were collected from the Lukmanier Pass area in the central part of the Swiss Alps. The occurrence of such garnets is restricted to specific lithostratigraphic levels characterized by thin alternations of quartz and mica-rich layers. Crystallization/deformation relationships indicate that the snowball garnets developed during a crustal thickening phase associated with N-NE directed movements. This phase locally produced a very strong crenulation cleavage and associated microlithons. Most importantly, the snowball garnets are commonly located on a line which corresponds to the crenulation lineation associated with this crustal thickening phase. This feature suggests that the onset of the garnet crystallization post-dated the microlithons formation.

Investigations of the chemical composition, crystallographic orientation, and three-dimensional shape of those garnets revealed several characteristics which enable us to better understand their formation. First of all, a detailed examination of the Mn pattern reveals a complex behaviour illustrated by anomalous high-Mn regions systematically located at the outermost edge of the bridges that connect two shells of snowball garnets. Considering Mn concentrations as time lines, this feature strongly suggests that static garnet crystallization along mica-rich layers subsequently connected the high-Mn regions of the same shell (Figs. 1 and 2). Secondly, evidence that the garnet porphyroblasts developed statically for a large part of their growing history is also attested by electron back-scattered diffraction (EBSD) analysis. Indeed, EBSD analysis of garnets reveals that most of the bridges have the same crystallographic orientation independently of their curvature. This observation means that the garnet crystallization took place once the micas rich layers have already been folded (Fig. 3). Thirdly, application of high-resolution X-ray computed tomography (μCT) imaging supports a final static garnet growth but highlights complex three dimensional spiral geometry such as predicted by rotational model of snowball garnet formation as well (Fig. 4). According to these observations, it consequently appears that the final growth history of those garnets was largely controlled by static crystallization.

As a consequence, the snowball garnet crystallization probably took place on the microlithons during the final stage of their formation. This feature suggests that the first step of the growth history likely occurred when the deformation was still going on and was accompanied by rotation, whereas the final growing stage mainly took place in a static regime.

We consequently interpret the spiral–shape geometry of the snowball garnets of the Lukmanier as the result of two different mechanisms. A first phase of simultaneous growth and rotation on pre-existing microlithons is followed by static crystallization along micas-rich layers. This interpretation suggest that although the geometry of the snowball garnet exhibits almost 300° of rotation, the true rotation undergone by the garnet is much less, a large part of the
spiral having been formed during the development of the microlithons.

Figure 1. X-ray image showing concentration of Mn in garnet from sample Luk_02_1.

Figure 2. Portion of X-ray image of Figure 1. Note the regions of high Mn at the outermost edges of the bridges that connect two shells of the garnet.

Figure 3. Crystallographic orientation map of garnet from sample Luk_02_7. Note that all the bridges have the same crystallographic orientation independently of their curvature.

Figure 4. 3-D imaging illustrating the complex spiral geometry of the snowball garnets.
Neotectonics in the Swiss Alps –

A postglacially active fault near the Gemmi Pass

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The area of the central and western Swiss Alps was chosen for examination of postglacial lineaments because it has the highest uplift rates of Switzerland (1.5 mm/a near Brig, Schlatter & Marti 2002) and shows a concentration of earthquake occurrence over the last 30 years (e.g. Baer et al. 2001). Aerial photographs from the whole area were searched for linear features, which could be of gravitational or tectonic origin. A number of lineaments were visited in the field to study their origin.

We found scarce but positive evidence for neotectonic fault movements. One lineament exhibited the most promising exposures and was investigated in greater detail.

This lineament is located at the Gemmi Pass. It is a prominent NW-SE striking fault revealing a long-lasting history of fault movements. It first was initiated as an open joint, where large amounts of fluids percolated precipitating large calcite crystals and blocky calcite cement. This joint fill was later overprinted with brittle deformation indicated by an up to 2 m thick cataclasite.

In addition, because of the displacement of Quaternary sediments, which overlay the fault in places, the fault was thought to have been reactivated in postglacial times. The position of the fault at the bottom of a large high-lying valley discounts gravitational reactivation. A 3-D georadar survey was carried out in an attempt to find evidence for recent movement of this fault (McClymont et al., this session).

The lineament transects a small (~60 m x 30 m) post-glacial, sediment-filled depression, which was targeted for the 3-D georadar survey. Two linear features were detected from time slices within the migrated data volume indicating potential fault strands.

For further investigation, a large trench was dug (15.4 m long, 2 m wide and up to 2.2 m deep). The trench bottom reached limestone bedrock for most of the length of the trench (x in Fig.1). It delineates a basin, that deepens towards the northeast.

The base of the sediment-fill of this depression is made of an up to 1.5 m thick dark brown moraine layer. The moraine material consists partly of lodgment till (h in Fig.1), partly of transported till (e, f and g in Fig.1). Large rock boulders (up to 1 m in diameter) were found in the till material.

A very constant 20 to 30 cm thick, fine grained (silt to fine sand fraction), yellow layer, for which the working term “loess” is used (d in Fig.1), was deposited on top of the moraine. It has a sharp upper contact, whereas the basal contact to the moraine material sometimes is unclear. This yellow layer delineates the basin form.

An up to 1.5 m thick grey-brown B horizon (b in Fig.1) of soil is overlaying the yellow loess layer. It consists of brown fine-grained silt material intercalated by numerous sand and grit lenses, and up to 7 m continuous clay bands, which are up to 5 cm thick (c in Fig.1). It shows onlap-structures onto the loess at both sides of the basin.

The uppermost 5 to 15 cm are made up by the active soil layer, the A horizon (a in Fig.1).

A cataclastic fault zone disrupts the partly karstified limestone bedrock from meter 6.4 to 6.8 m. This 40 cm wide zone is split in the middle by an open joint or faultplane. No surface displacement was seen on the bedrock surface.

Right above this fault zone, the about 50 cm thick moraine layer does not show any disturbances. But the yellow loess layer, which represents a very continuous horizon with a clear upper surface, is heavily disrupted, incorporating moraine material from below.
and displaying flame-like structures and up to 5 cm large vertical displacements at its upper boundary. These structures cannot be explained by any sedimentary or erosional processes. The overlaying B horizon does not seem to be displaced at all (Fig. 1), thus sealing the movement.

These observations indicate a strike-slip event, which would also be consistent with the present-day stress-field. An earthquake in 1996, which happened about 5 km SW of this location, displayed vertical NNW-SSE and ENE-WSW striking focal planes with strike-slip movement (Baer et al. 1997).

Samples for OSL-dating of the Loess layer and the B horizon were taken in order to limit the age of the movement.

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Changes in the north-Alpine climate as a function of the Alpine upliftment: constraints from isotopic compositions of fossils and sediments of the Molasse, and Alpine vein quartz


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While much is known about the geological-geochronological framework of Alpine tectonism, including associated erosional rates and sediment volumes, estimates of changes in paleoelevation and its direct influence on paleoclimate have been less well constrained. Over the course of the past several years this relationship has been examined on the basis of combined geochemical-isotopic studies of the Tertiary northern Alpine Molasse sediments. These sediments were deposited in marginal basins that were partly to completely isolated from other major oceanic basins during major periods of Alpine tectonism but also at a time of large global climatic change. As will be outlined below, they are well suited to study the effects of tectonic forcing on regional climate. By comparing the past climatic and oceanographic evolution indicated by the Molasse sediments to those on a global scale, a qualitative evaluation of the relationship between tectonism and regional climate is made possible.

One approach to determine changes in paleoelevation is to investigate the hydrogen (and oxygen) isotopic composition of clay minerals within the Molasse sediments. It has been known for some time, that the H and O isotope composition of clay minerals formed in a weathering environment reflects that of the average ambient precipitation (e.g., Lawrence and Taylor, 1971). The H- and O-isotopic composition of precipitation, in turn, is largely controlled by mean ambient air temperature, which in mountainous regions is itself directly related to the mean elevation (e.g., Schürch et al., 2003). Hence, the H- and O-isotopic composition of clay minerals derived from the Alps as weathering material and deposited as detritus in the Molasse sediments may be used as a proxy for climatic and/or topographic changes in the source terrain (e.g., Chamberlain and Poage, 2000). The H-isotope composition of the less than 2 μm size fraction sampled from drill-cores in the German Molasse changes throughout the two transgressive-regressive cycles of Molasse deposition from average δD values (relative to VSMOW) of about −66‰ in the Lower Marine Molasse to −77‰ in the Lower Freshwater Molasse, −71‰ in the Upper Marine Molasse, and reaching values as low as −98‰ in the Upper Freshwater Molasse. Hence, clays in both freshwater cycles have lower values compared to those from the preceding marine units. This change in the H isotope composition would be compatible with decreasing temperatures throughout sedimentation from the Late Oligocene up to the Late Miocene and/or with several phases of upliftment of the source terrain. A cooling trend is in agreement with the overall global cooling during the Tertiary. Isotopic composition of precipitation estimated to be in equilibrium with the clay minerals is compatible with a source terrain changing in average elevation of weathering from about 500 to 1200 m, given a typical altitude effect for the precipitation as is observed for recent precipitation sampled in Switzerland (Schürch et al., 2003).

A completely independent approach to estimating past changes in elevation is given by isotopic analysis of vein and fissure quartz formed during retrograde metamorphism in Alpine rocks (e.g., Mullis et al., 2001). Several distinct groups of vein and fissure quartz can be differentiated on the basis of their occurrence, textural appearance, and composition of included fluids. Sometimes, these distinct generations of quartz even occur within the same fissure. While fluids calculated to be in equilibrium with early Tessin-habitus quartz, formed at 450 to 410 °C and 3.5 to 2.2 kbars, has O isotope compositions and H isotope compositions of its included fluids that are typical of metamorphic fluids (+6 to +23‰ and +7 to −70‰, respectively), late stage split-growth quartz, formed at about 250 to 180 °C and 1.2 to 0.5 kbar, approaches isotopic compositions that are clearly in
equilibrium with meteoric fluids: quartz $\delta^{18}O$ values as low as $-3.7\%$, with corresponding fluid $\delta^{18}O$ values between $-7$ and $-16\%$ and measured $\delta D$ values between $-78$ and $-140\%$). Again using recent altitude effects as an analogue, these isotopic compositions would imply paleotopographic highs during the Mi-Miocene in excess of 3500 m for the Gotthard massif area.

A third, recently discovered indicator of the paleotopography is based on the analysis of fish teeth, in this case “exotic” shark teeth from Swiss Upper Marine Molasse sediments. Two teeth out of six measured had $\delta^{18}O$ values (VSMOW) of about $11\%$, values completely different from teeth of the same species sampled in the same locality (La Molière; 20.7 to 21.8%). These exotic teeth also had Sr isotope ratios compatible with a freshwater, Jurassic carbonate-dominated composition, which is in contrast to that for the other teeth that have more typical Miocene marine compositions. All teeth, however, have the same types of REE patterns, supporting the same marine pore-fluid type diagenetic history. Thus, a freshwater formation for the exotic teeth is postulated and, assuming a similar habitat temperature for these sharks, suggests $\delta^{18}O$ values for water of about $-10\%$, hence minimum altitudes of about 1500 m.

These three independent lines of evidence, collectively indicate significant changes in altitude of the Alps during the Oligocene to Miocene, with average altitudes of about 1500 to 2000 m and peak elevations in excess of 3500 m during the Late Miocene, that is elevations similar to those of today.

Paleoclimatic reconstructions from North Alpine Molasse sediments are based on oxygen isotope compositions of fossil mammalian tooth enamel for freshwater molasse deposits, and shark teeth, marine ostracoda, foraminifera, and mammalian phosphatic fossils for the Upper Marine Molasse deposits. The $\delta^{18}O$ values (VPDB) of carbonate in phosphate from Oligocene and Miocene large mammal teeth (n=270), for example, vary over a large range from $-11.9\%$ to $-0.5\%$, but these variations parallel the composite O isotope curve of Tertiary benthic foraminifera from the Atlantic ocean, thus similarly reflecting major global climatic changes such as the Late Oligocene warming, Middle-Miocene climate optimum, and Middle to Late Miocene cooling trends. The $\delta^{18}O$ values (VSMOW) of phosphate in shark teeth (19.5 to 23.5%, n=155) from Miocene marine Molasse sediments as well as those of ostracods and foraminifera from these sediments all have variations that also parallel those of composite curves for global changes (e.g., Vennemann and Hegner, 1998; Janz and Vennemann, 2005). In addition, the Sr-isotope compositions of these marine fossils largely support open marine conditions, indicating that the marginal basins had good connections to the open oceans. Exceptions do exist for some localities, most notably those situated close to old siliceous massifs, where a local input of Sr was important during certain periods.

Collectively, the data support a paleogeography for the Tertiary Alps represented by a high mountain belt with altitudes similar to that of today adjacent to marginal marine or freshwater depositional basins but with a regional climate, at least for the northern Molasse realm, that was strongly coupled to the global climate. The Alps thus appear not to have influenced the local climate and/or atmospheric circulation patterns significantly at this stage. Further investigations will focus on north-south comparisons of climatic change across the Tertiary Alps.

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