Emile Argand Conference – EGU series

12th ALPINE WORKSHOP

13-19 September 2015

Montgenèvre / Briançon – French Hautes-Alpes

ABSTRACT VOLUME

Organization: **Christian Sue (csue@univ-fcomte.fr)**
Gianreto Manatschal (manat@unistra.fr)
Raymond Cirio (cirio.raymond@wanadoo.fr)

alpine-workshop*-briancon-2015.eu*

On the Ladinian magmatism in the Dolomites (Southern Alps)

Abbas Hassan[1], Lustrino Michele[1], Agostini Samuele[2], Gianolla Piero[3], Carminati Eugenio[1]

1 P.le A. Moro 5, Roma, Italy, Dept. Of Earth Sciences, University of Roma "La Sapienza" (hassan.abbas@uniroma1.it, michele.lustrino@uniroma1.it, eugenio.carminati@uniroma1.it)
2 Via Moruzzi 1, Pisa, Italy, Istituto di Geoscienze e Georisorse, CNR (s.agostini@igg.cnr.it)
3 Via Saragat 1, Ferrara, Italy, Dept. of Physics and Earth Sciences, University of Ferrara (piero.gianolla@unife.it)

Magmatic activity is widespread in the Southern Alps during Middle Triassic, with a peak registered during Ladinian. In the Dolomites area huge amounts of volcanic, volcaniclastic and plutonic rocks crop out, interbedded within and cutting through shallow water carbonates and deeper water sediments. In the Alpe di Siusi, Marmolada and Latemar areas generally fresh mildly alkaline potassic volcanic rocks have been sampled and analyzed.
The rocks are characterized by porphyritic and glomerophyric texture with fine to medium grained hypohyaline to hypocrystalline groundmass. Plagioclase is the most common phase, with compositions ranging from rare andesine to more common labradorite and bytownite (Ab13-60An36-86Or1-8). Alkali feldspar is slightly less common, represented by sodic sanidine in Latemar and Alpe di Siusi (Ab25-46An2-9Or53-69). Only in the Predazzo granite the alkali feldspar is almost pure orthoclase (Ab5-11An0Or89-96). Clinopyroxene is a common phase in all the samples but the Predazzo granite. This phase shows relatively uniform augite composition (Wo40-46En35-43Fs12-22). Only Fe-Ti oxides belonging to the spinel solid solution have been measured with ulvöspinel molecule ranging from 10 to 65%. Olivine crystals are found in a few thin sections as iddingsite pseudomorphs.
These rocks are basic in terms of silica content (SiO_2 = 49.8-52.4 wt%, LOI-free basis), with compositions ranging from potassic alkali basalt to potassic trachybasalt and shoshonite, with K_2O/Na_2O ratios ranging from 0.76 to 2.03. Despite the relatively small spread in SiO_2, the investigated rocks are characterized by a large range of Al_2O_3 (14.3-19.8 wt%), Fe_2O_3tot (8.1-13.1 wt%), MgO (3.0-7.7 wt%), CaO (6.9-10.6 wt%), Na_2O (1.9-3.5 wt%) and relatively smaller variation of the other major elements. The Predazzo granite (SiO_2 = 75 wt%; MgO = 0.1 wt%; ASI = 1.02) enlarges the chemical range of the igneous rocks of this area. Crystal-vitric hyaloclastites tuff also with completely glassy shards crop out in the Alpe di Siusi. The composition of these glasses is very variable, with much more alkaline, more potassic and differentiated compositions (tephri-phonolite, latite and trachyte) compared to the other volcanic rock samples from the same area.
Primitive mantle-normalized (PM) multielemental patterns are homogeneous for the different rock types analyzed, resembling typical subduction-related igneous rock compositions. The key features of the pattern are medium to high amounts of LILE (with Rb, Ba, Th and U contents mostly 70-150 times PM estimates), deep Nb-Ta troughs (15-23 times PM), small peaks at K (75-160 times PM), common, but variable peaks at Pb (~40-125 times PM), small troughs at Ti (~6-8 times PM) and very flat HREE. In particular, the investigated rocks show very homogeneous and not strongly fractionated LREE/HREE ratios, with not strongly variable La (95-138 times CI chondrite) and Lu content (~11-14 times CI). The strongest fractionation is observed between LREE and MREE, with La_N/Gd_N ranging from 3.9 to 5.2 and nearly flat MREE/HREE ratios (e.g., Tb_N/Lu_N = 1.0-1.6). The Predazzo granite shows a much more spiked pattern, with much higher LILE content (Rb, Th, U ~800-900 times PM), very low Ba (~6 times PM), Sr and P (~1 time PM), Eu (~2 times PM) and Ti (~0.5 times PM), and with flatter and higher HREE.
On the basis of the petrography, mineral chemistry (e.g., Ti-Na-poor clinopyroxene), major element (e.g., Ti-Fe-poor, K-rich) and trace element content (e.g., Nb-Ta troughs, K and Pb peaks in primitive mantle-normalized diagrams, and generally high LILE/HREE and LILE/HFSE ratios) these rocks resemble typical magmas emplaced along active margins, above subduction systems. The igneous activity, associated with very fast subsidence represented by the very thick accumulation of shallow carbonates is at odd with a continental rifting setting.

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Low-temperature evolution of the inner sector of the Cottian Alps (Western Alps, Italy): evidence from Ap and Zr (U-Th-Sm)/He analysis

Bacenetti Marco[1], Stockli Daniel[2], Cadoppi Paola1,[3], Gianluigi Perrone[1]

1 Department of Earth Sciences, University of Torino, via Valperga Caluso 35, 10024 Torino – Italy; marco.bacenetti@unito.it
2 Jackson School of Geosciences, The University of Texas at Austin, Austin, TX
3 Research Centre on Natural Risks in Mountain and Hilly Enviroments (NatRisk) - University of Turin

Late-stage exhumation of the Alps is understood as the interplay of tectonics and erosion (Willett, 2010). While the former has been influenced by a decrease in plate convergence, the latter is more likely controlled by climatic variation (Vernon et al., 2008). The influence of each of these processes and their potential interrelations are still debated.
For this study, we investigated the late stage exhumation history of the inner sector of the Cottian Alps (Western Alps, Italy). The area is affected by a diffuse seismicity of generally low magnitude (ML> 3, with rare events of greater magnitude) characterized by shallow hypocenters

(< 20 Km depth). From tectonic point of view the Western Alps is characterized by a widespread extensional regime located in the core of the belt and a dominant transcurrent tectonic regime at the outer borders of the chain, with some local compressive areas.
Western Alps have been broadly sampled for thermochronological analyses at the regional scale. In particular, using apatite fission-track thermochronometers, previously published data (Cadoppi et al., 2002, Carrapa et al., 2003, Beucher et al., 2012) indicate slow rates (<0.2 km m.y.-1) of erosional exhumation across the Western Alps during Oligocene-Miocene times (~30–10 Ma).
Here we present a new dataset create using (AHe) apatite and (ZHe) zircon (U-Th-Sm)/He thermochronometers. The dataset including 13 AHe and 15 ZHe ages, respectively. Sample were collected along a north-south pseudo-vertical bedrock profile (elevation between 650 and 2850 m) resulting in a total elevation difference of nearly 2.2 km. The profile is locate into the central part of the inner Cottian Alps (Germanasca valley).
In the study area outcrop the Dora-Maira unit (DM) that represent, together with the Gran Paradiso and Monte Rosa Massifs, the basement nappes of the inner Penninic Domain (also called Internal Crystalline Massifs). The DM (review and references in Sandrone et al., 1993) is a continental crust unit consisting of an upper complex formed of pre-Carboniferous metasediments (with minor metabasites) and a lower complex composed of Permian-Carboniferous metasediments. Both complex contain meta-intrusives of granitic to dioritic composition, in most cases related to the late Variscan magmatic event.
For all samples three to six aliquots were analyzed. Raw (U-Th-Sm)/He ages were corrected for alpha ejection at the crystal surfaces. ZHe ages range from 32.2±5.64 Ma to 19.1±1.40 Ma. The AHe ages ranging from 20.7±2.30 Ma to 3.7±1.49 Ma.
First results from AHe and ZHe, in combination with the existing thermochronological data, suggest that since the late Oligocene the evolution is characterized by two main stages. Between ~ 30 Ma and 20 Ma, the new thermochronological data show linear trend of exhumation history; from ~ 20 Ma to 3 Ma data shows a more complex trend with overall decreasing exhumation.

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Pre-Alpine (Variscan) inheritance: a key for the location of the future Penninic front (Western Alps)

Ballèvre Michel, Manzotti Paola, Poujol Marc

Géosciences Rennes, Université de Rennes1, 35042 Rennes Cedex (michel.ballevre@univ-rennes1.fr)

The boundary between the Dauphinois-Helvetic domain and the Briançonnais domain has long been recognized as a major fault zone (“Penninic front”) in the Western Alps, based on the differences in the Mesozoic stratigraphy on both sides of the fault. Some differences in the pre-Alpine basement were also recognized up to the 70’s. With the advent of the plate tectonics models, emphasis was put on the interpretation of the Mesozoic sequences, as recording the structure of the European palaeomargin. A (narrow) oceanic domain has been postulated at least along part of this boundary (the Valaisan ocean), but its existence, nature and age have been disputed. These debates have obscured the information provided by the pre-Alpine basement, on which this contribution will focus.
Three lines of evidence suggest that this boundary also represents a significant pre-Alpine tectonic boundary that has been reactivated at different times since the Triassic.
1. The metamorphic history of the pre-Alpine basement shows significant differences between the External Massifs (Argentera, Pelvoux, Belledonne, Aiguilles Rouges –Mont Blanc, Aar) and the basement of the Briançonnais zone (Vanoise, Grand Saint Bernard, Dora-Maira, Gran Paradiso, Monte Rosa).
2. A major coal-bearing basin (the “Zone Houillère”) opened along this boundary. This basin extends for about 150 km in length and a width of about 10 km. Even without taking into account its Alpine deformation, it is one of the largest Carboniferous basins inside the Variscan belt. It is a limnic basin (not a surprise for an intra-montane basin) and its tectonic origin has never been properly investigated. The Zone Houillère is not comparable with the external, paralic (flexural) basins on both sides of the Variscan belt, but shows similarities with the Saar-Nahe basin. Like the latter, we interpret the Zone Houillère as a transtensional basin opened along a major, crustal-scale, fault zone. New data will be provided on the detrital zircon geochronology in the Carboniferous sequences from the Briançonnais microcontinent (2 samples from the Money window (see Manzotti et al., 2015), another set of 2 samples from the Pinerolo window, and 1 sample from the Zone Houillère itself (from Briançon). About 120 grains were analyzed in each sample, allowing a representative assessment of the various (and contrasting) sources involved during the erosion of the Variscan belt.
3. The Permian magmatism and sedimentation display-contrasting distributions, being absent or very localized in the Dauphinois domain, and widespread in the Briançonnais domain. From the petrological

characteristics of this magmatism, major differences can be inferred in the thermal state of the subcontinental mantle and the overlying lower crust.
The data will be integrated into a tectonic model of the Variscan belt, emphasizing how the Variscan inheritance plays a major role in defining the future boundary between the European palaeomargin and the Briançonnais microcontinent.

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Very hot, very shallow hydrothermal dolomitization: an example from the Maritime Alps (NW Italy-SE France)

Luca Barale[1], Carlo Bertok[1], Namam Salih Talabani[23], Anna d'Atri[1], Luca Martire[1] Fabrizio Piana[4], Alain Préat[2]

1: Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, 10125 Torino. luca.barale@unito.it
2: Department of Earth and Environmental Sciences, Université Libre de Bruxelles, 50, avenue F. D. Roosevelt, CP 160/02. B-1050 Brussels.
3: Petroleum Geosciences Department, Soran University, Delizian
4: CNR IGG – Torino, Via Valperga Caluso 35, 10125 Torino.

In the Maritime Alps (NW Italy–SE France), the Middle Triassic and Middle Jurassic–Berriasian platform carbonates of the Provençal Domain locally show an intense dolomitization. Dolomitized bodies vary in size from some metres to hundreds of metres, and are associated with tabular bodies of dolomite-cemented breccias, cutting the bedding at a high angle, and networks of randomly oriented dolomite veins. Field and petrographic observations indicate that dolomitization was a polyphase process, in which episodes of hydrofracturing and host-rock dissolution, related to episodic expulsion of overpressured fluids through faults and fracture systems, alternated with phases of host-rock dolomitization and void cementation. In thin section, main dolomite types are finely- to medium-crystalline, planar-s replacement dolomite, and coarsely-crystalline saddle dolomite occurring both as cement and replacement phase. Fluid inclusion analysis indicates that dolomitizing fluids were relatively hot (170–260 °C), whereas the stratigraphic frame documents the very shallow burial setting of dolomitization, which occurred in the earliest Cretaceous. Collectively, these pieces of information compose the overall picture of a large-scale hydrothermal system related to deep-rooted faults, and provide indirect evidence of earliest Cretaceous fault activity in this part of the Alpine Tethys European palaeomargin. The study case represents an outstanding example of a fossil hydrothermal system, which can represent a reference for recognizing the main geometric and petrographic features of hydrothermally dolomitized rocks.

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Stratigraphic and tectonic setting of the southern termination of the Western Alps (Ligurian-Maritime Alps junction): an update

Barale, L.[1,3], Bertok, C.[1], d'Atri, A.[1], Martire, L.[1], Piana, F.[2], Rossetti P.[1]

1 Dipartimento di Scienze della Terra, Università di Torino, Italy
2 CNR-IGG, Istituto di Geoscienze e Georisorse, Torino, Italy
3 Gi-RES srl, "spin-off " company of CNR-IGG, Torino, Italy
e-mail address: f.piana@csg.to.cnr.it

A revision of the stratigraphic and tectonic setting of the southern termination of the Western Alps, at the junction of the Maritime Alps with the westernmost Ligurian Alps, is proposed. In response to the Alpine kinematic evolution a number of tectonic units individuated on the deformed palaeo-European continental margin and were arranged in a NW–SE anastomosed pattern along the NE boundary of the Argentera Massif. These tectonic units often cut across the paleogeographical subdivision of the Alpine literature and show only partial affinity with their distinctive stratigraphic features. The tectono-sedimentary evolution of the studied units is discussed: in the Cretaceous it was characterized by intense tectonic controls on sedimentation inducing lateral variations of stratigraphic features and major hydrothermal phenomena, while since the early Oligocene, a transpressional multistage tectonics induced a NE–SW shortening, together with significant relative left-lateral and then (late Oligocene–middle Miocene) right-lateral movements along E–W to SE–NW direction. This induced the juxtaposition and/or stacking of Briançonnais, Dauphinois and Ligurian tectonic units characterized by different metamorphic histories, from anchizonal to lower greenschist facies. This evolution resulted in the arrangement of the tectono-stratigraphic units in a wide "transfer zone" necessary to allow the Oligocene westward indentation of Adria promontory, the counterclockwise rotations at the south-western termination of Western Alps and the Miocene, SE-directed, right-lateral tectonics, coeval with the Argentera Massif uplifting.

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Thermal and structural evolution of the Alpine collisional wedge (External Crystalline Massifs, Western Alps)

Bellahsen N.[1], A. Boutoux[1], Y. Rolland[2], A. Verlaguet[1], R. Pik[3], M. Bellanger[4], L. Jolivet[4], R. Augier[4]

1 ISTEP, Sorbonne Universités, UPMC Paris CNRS, UMR 7193 France
2 Géoazur, UNSA, CNRS, UMR 7329, Valbonne, France.
3 CRPG, Univ de Lorraine, CNRS, , Vandoeuvre-Lès-Nancy, France.
4 ISTO, Université d'Orléans, CNRS, UMR 7327, France

Collisional wedges are usually described by analogy with the frictionnal wedge that captures well the characteristics of oceanic accretion wedges or collisional fold-and-thrust-belts. However, all well-documented orogens show that ductile deformation occurs especially at mid and deep-crust. Yet, the precise effect of deep ductile crustal levels on wedge evolution is still poorly understood and this precludes a complete understanding of the kinematics and mechanics of (brittle-ductile) orogenic wedges.
In this contribution, we present and synthesize recent and new results on the thermal and structural evolution of the external zone in Western Alps: thermochronological, thermal, geochronological, and structural data from the Mont Blanc/Aiguilles Rouges massifs to the Oisans/Grandes Rousses massifs (External Crystalline Massifs, ECM).
We show that, from south to north, the amount of crustal shortening significantly increases in the external zone, quantifying and witnessing a more localized shortening in the north than in the south. At the same time, the collisional temperature peak slightly increases from south to north, which may at least partly explain these structural differences (Bellahsen et al., 2014).
Our results also show that, from south to north, there are also a number of striking similarities. Among them, in both massifs (Mont Blanc in the North and Oisans in the South), distributed shear zones have been mapped: the well-known Mont Blanc Shear Zone and the recently mapped Oisans and Grandes Rousses shear zones. The Mont Blanc shear zones have been formed from 30 to 16 Ma (Rolland et al., 2008; Cenki-Tok et al., 2013) at a temperature of about 400°C. The Oisans and Grandes Rousses shear zones formed between 33 and 25 Ma at about 350°C (Bellanger et al., 2015).
A frontal crustal thrust is also inferred from cross section balancing and geophysical data below each frontal ECM. Such structure can most likely be considered as a more localized feature than the distributed shear zones described above.
Another similarity is then a rather long thermal peak (5 to 15 Ma, depending on the area) that seems to be synchronous with the significant stage of shortening of the ECM. As a consequence, this shortening event does not cause any exhumation and cooling. The cooling started with the frontal ramp activation and witnesses the accretion (mostly by underplating) of units to the collisional wedge.
We propose a 3-step evolution.
(1) The European proximal margin (Dauphinois) is underthrusted at 30-35 Ma below the proto-collisional wedge (internal zone).
(2) The crust is shortened at depth with no significant burial or exhumation (probable thermal peak, Oligocene-lower Miocene). The shortening is distributed.
(3) The exhumation and cooling started (at around 16 Ma) because of the activation of frontal thrusts that also activate cover décollement and create the subalpine chains. This phase corresponds to the underplating event and the accretion of tectonic units s.s.

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From rift-inherited hyper-extension to orogenesis: De-coding the axial zone of orogenic belts

Marco Beltrando[1], Gianreto Manatschal[2], Geoffroy Mohn[3], Giorgio Vittorio Dal Piaz[4], Alberto Vitale Brovarone[5], Emmanuel Masini[6]

(1) Dipartimento di Scienze della Terra, Università di Torino, Torino, Italy (marco.beltrando@unito.it), (2) IPGS, CNRS-EOST, Université de Strasbourg, Strasbourg, France, (3) GEC, Université de Cergy-Pontoise, Cergy, France, (4) Accademia delle Scienze di Torino, Torino, Italy, (5) IMPMC, Université Pierre et Marie Curie, Paris, France; (6) TOTAL, CSTJF, Pau, France

The relative role of rift-inherited hyper-extension and subduction/collisional dynamics in establishing the lithostratigraphic associations and overall architecture of orogenic belts has been investigated in the Western Alps and Corsica. This case study was selected to test existing models involving complex subduction/exhumation dynamics to account for seemingly chaotic mixing of continental crust and serpentinized mantle rocks in high-pressure metamorphic units.
The methodology developed to assess the role of rift-inheritance in multiply deformed-metamorphosed tectonometamorphic units stems from recent advances in the understanding of hyper-extended domains in present day magma-poor rifted margins, where the crustal architecture displays transitional features between typical oceanic and continental domains. In these areas, slivers of hyper-extended continental crust or pre-rift sediments may rest as extensional allochthons upon serpentinized mantle, while syn- and post- rift sediments seal the extension-related lithostratigraphy.
Following multi-stage orogeny-related deformation and metamorphism, this rift-related lithostratigraphic architecture can erroneously be ascribed to complex subduction dynamics, partly due to the sliver-like appearance of continental basement. However, the partial preservation of rift-related lithostratigraphic associations may still be assessed by (1) the consistency of the

lithostratigraphic architecture over large areas, based on the continuity of key surfaces (i.e. base of early post-rift sediments) across the orogeny-related macro-structures, (2) the presence of clasts of basement rocks in the neighboring meta-sediments, indicating the original proximity of the different lithologies, (3) evidence of brittle deformation in continental basement and ultramafic rocks pre-dating Alpine metamorphism, indicating that they were juxtaposed by fault activity prior to the deposition of post-rift sediments, and (4) the similar Alpine tectono-metamorphic evolution of ophiolites, continental basement and meta-sediments.

The partial preservation of rift-related relationships despite subduction to (U)HP conditions indicates that the association of serpentinites and continental basement, which in the Western Alps has often been ascribed to chaotic counter-flow in a subduction channel, may also be an inherited feature from the rifting history. Within this context, the high-pressure Alpine tectono-metamorphic units were probably detached from the downgoing lithosphere along a hydration front that is typically observed in present-day distal margins.

The relationship between the architecture of the Jurassic rifted margins and the distribution/extent of Alpine metamorphism indicates that the axial zone of the Western Alps, which records multi-stage deformation and high pressure metamorphism, originated from the hyper-extended rifted margins of the European and Adriatic and from the intervening magma-poor ridge system. Relative plate motion during Cretaceous–Tertiary inversion was largely accommodated at the transition between hyperextended domains, floored by extremely thinned crust or hydrated subcontinental mantle, and proximal domains consisting of thicker continental crust. As a result, distal hyper-extended margins were preferentially subducted, whereas the proximal domains underwent relatively minor deformation and metamorphism. The final stage of continent-continent collision was achieved following subduction of the distal European margin, when the European necking zone reached the subduction zone.

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A crustal-scale view at rift localization along the fossil Adriatic margin of the Alpine Tethys (Italian Southern Alps)

Beltrando Marco[1], Stockli Daniel F.[2], Decarlis Alessandro[3], Manatschal Gianreto[3]

(1) Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, 10125 Torino, Italy (marco.beltrando@unito.it);
(2) The University of Texas at Austin, Department of Geological Sciences, 1 University Station C1100, Austin, TX 78712, USA.
(3) IPGS – EOST, Université de Strasbourg, CNRS UMR 7516; 1, rue Blessig F-67084, Strasbourg, France

Fossil rifted margins, whereby originally extended continental crust is subsequently stacked in orogenic belts, provide the opportunity to track rift-related tectonics across different crustal levels. In this study, the tectono-thermal evolution of the fossil Adriatic continental margin, sampled in the Italian Southern Alps, is investigated combining new (U-Th)/He zircon (ZHe) thermochronology from upper crustal rocks with existing data from the originally underlying lower crust, to shed light on the processes responsible for rift migration and localization in the Alpine Tethys system. The Adriatic micro-plate was selected as it records a protracted rift evolution, whereby distributed upper crustal stretching at 245-195 Ma was followed by westward rift migration, culminating in mantle exhumation at ca. 165 Ma.

Samples were collected from the Permian igneous rocks directly below Mesozoic basins, so that paleodepths throughout the Mesozoic could be estimated. A progressive westward younging of ZHe ages, from 280-240 Ma in the Lombardian basin to 215-200 Ma near the Sostegno and Fenera basins, indicates that thermal gradients >60-70°C/km were locally established in the upper Triassic along the future western edge of the Adriatic plate. This heating-cooling cycle was contemporaneous with extensive fluid percolation at 220-200 Ma, coupled with minor magmatism and shearing, within the originally underlying lower crust, sampled in the Ivrea Zone. Normal faulting at upper crustal depths was initiated post-185 Ma, as constrained by exhumation-related ZHe ages in detrital zircons from a syn-tectonic sandstone.

Therefore, the onset of rift-related deformation at the future western edge of the Adriatic plate, recorded only at lower crustal depths, was coeval with a localized crustal-scale thermal anomaly. Starting from ca. 185-180 Ma, extension spread to all crustal levels, as the activity of W-dipping normal faults at the surface was coeval with shearing along the E-dipping Pogallo shear zone, at mid-crustal depth. The resulting crustal necking was then followed by complete crustal excision and mantle exhumation, now observed in the Canavese Zone. The picture of the evolving western edge of the Adriatic plate arising from this study suggests that rift focussin was favored by thermally-driven strain softening of the lithosphere.

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Eo-Alpine evolution in the Eastern Alps under brittle conditions revealed by Monazite Th-Pb dating

Christian Bergemann[1], Edwin Gnos[2], Alfons Berger[3], Martin Whitehouse[4], Franz Walter[5], Hans-Peter Bojar[6]

1- University of Geneva, Geneva, Switzerland (christian.bergemann@unige.ch)
2- Natural History Museum of Geneva, Geneva, Switzerland
3- University of Bern, Bern, Switzerland
4- Swedish Museum of Natural History, Stockholm, Sweden
5- University of Graz, Graz, Austria
6 -Universalmuseum Johanneum, Graz, Austria

The temporal evolution of areas that experienced multiple phases of brittle deformation is complex to unravel.

Brittle structures in Austroalpine areas to the east of the Tauern Window, Austria, are an example of this [1, 2]. In the Schoberpass-Mautern region thrusting of Carbonifeours sediments of the Grauwackenzone over Permian clasitic rocks of the Rannachserie occurred during regional metamorphism and was followed by transtensional tectonic movements associated with the formation of the Gosau basins. Thrusting led to hydrothermal vein and cleft formation in more competent dolomitic layers of the Grauwackenzone and the Rannachserie. Some rare clefts contain monazite in association with dolomite ± calcite ± quartz ± sulfide minerals. High precision SIMS isotope dating of the different growth domains in monazites from these cavities yields 232Th-208Pb crystallization ages spanning a total time of around 20 Ma from ~90 to ~70 Ma. The spatial distribution of age spots in the analyzed monazites, combined with chemical zoning, indicate stepwise growth likely linked with repeated dissolution reprecipitation processes. Despite the fact that the clefts are located close to the Salzach-Ennstal-Mariazell-Puchberg fault (SEMP) and the Polten-Liesing fault (PLF), which both show strong Neogene brittle tectonic activity [3], the eo-Alpine evolution is recorded and preserved in the clefts whereas the Neogene deformation does not affect the isotopic system of the older monazites. The oldest eo-Alpine ages coincide with nappe stacking in the area. Renewed monazite crystallization occured during transtensional movements [2] in association with basin formation and sedimentation of the Cretaceous Gosau Group. The faults investigated provide a link from the Cretaceous on to fault zones and sedimentary basins documenting subsequent Neogene activity. This suggests multiple activity of these fault zones. The dating of minerals preserved within cavities in hydrothermal-brittle systems provides a promising tool to reconstruct such multiphase evolution.

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Structural changes from very proximal to distal European margin (Central Alps) and their effect on Alpine collision

Alfons Berger and Marco Herwegh

Institute for Geology, University of Bern, Baltzerstr. 1+3, CH-3012 Bern; alfons.berger@geo.unibe.ch

The reconstruction of European proximal basement units is used to discuss the inheritance of pre-alpine structures for the inversion of the passive continental margin during Alpine collision. The role of tectonic preconditioning of rifted margins during their inversion has been intensively investigated for ocean-continent transitions (e.g., Mohn et al. 2012 and literature therein). In this study, we compare the tectonic evolution between an ocean-continent transition versus the very proximal continental margin. This comparison requires the identification of the major paleogeographic units within a transect ranging from the internal to the external proportions in both map- and section view. Retrodeformation of a cross section through the central Aar-massif, adjacent European basement and Valaisan units allow to unravel the effect of rift-related geometries for Alpine deformation of the distal and proximal European margin. During an early stage, the distal margin underwent thick-skinned nappe stacking of units in 3-5 km thickness. This piling up is favored by the rift-related thinning of the continental crust at the transition to the Valais trough. In contrast, the proximal margin has a thickness characteristic for a normal continental crust, which acts as a backstop at that time. In the later collisional stage, also the proximal European margin (external massifs) became integrated into the Alpine orogen, whereas the already thickened distal margin underwent crustal scale folding. The basic difference in the deformation style between former distal and proximal passive margins is based on different responses of the varying crustal- and lithospheric-mantle thicknesses on the shortening. Particularly the buoyancy of the thick proximal margin prevents its subduction to substantial depths provoking a reduced convergence rate.

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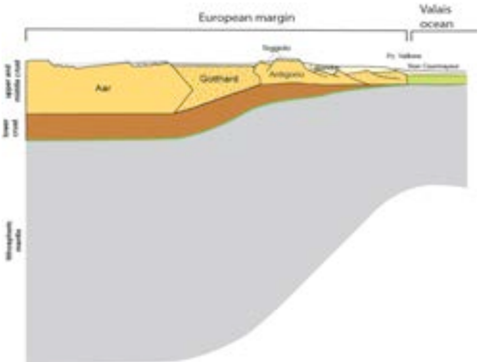

Sketch of the European continental margin, indicating the difference in crustal and mantle thickness

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Reconciling late fracturing over the entire Alpine belt: from structural analysis to geochronological constrains

Audrey Bertrand[1], Christian Sue[2]

1- Geological, Geophysical and Space Science Research Group of the Hungarian Academy of Sciences, 1/C Pázmány P. Sétány, H-1117, Budapest, Hungary (audreybertran@gmail.com)

2- Laboratoire Chrono-Environnement, UMR 6249, Université de Franche-Comté, Besançon, France

Brittle deformations allow assessing the late stage of deformation of an orogenic chain. The main aim of this work is to reappraise the meaning of the late fracturing over the entire Alps in a global geodynamic context. However, in order to compare the brittle deformations belonging to different areas, the age of these deformations is of first importance. The closure temperature of fission tracks in zircon crystals corresponds to the brittle-ductile transition temperature in quartz in basement rocks. Therefore, at first approximation, the maximal age of brittle deformation can be inferred from zircon fission track ages. Over the entire Alps, numerous studies focused on brittle deformation show similarities in the orientation of the main stress axes. Combined analyses of zircon fission tracks cooling ages of basement rocks with paleostresses data allow the comparison of the brittle deformations .

In the Western Alps, paleostress datasets indicate a major occurrence of orogen-paralell extension and associated strike-slip regimes both in the Valais-Vanoise area (Champagnac et al. 2006; Sue et al. 2007) and in the Briançonais area (Sue and Tricart, 2003). Indeed, paleostress data show a rotation of the main σ3 stress axes with the bending of the belt. Those structures are of Miocene age and are related to the propagation of the Alpine front toward the external alpine domains.

In the Central Alps, Paleostress fields are dominated by orogen-parrallel extensional regimes both in the Bergell area (Ciancaleoni and Marquer 2008) and the Lepontie dome (Allanic, 2012). In those areas, the brittle structures are assumed to be related to the formation of large-scale upright folds, that accommodate most of the collisional shortening due to the north-directed component of the movement of the south alpine indenter (Schmid et al., 1996).

In the Eastern Alps, the only area of the Eastern Alps where the zircon fission track ages are of Tertiary ages is the Tauern Window. The brittle deformations of the Tauern Window are dominated by orogen-parallel extension at the eastern and western borders of the dome and by strike-slip faulting in the central parts of the dome (Bertrand et al., 2015). In the Eastern Alps, orogen-parallel extension is inferred to be driven by the combined collapse and lateral escape of the orogenic wedge, due to indentation on the Adriatic indenter (Ratschbacher et al., 1991).

When looking at the brittle tertiary deformations, the major orogen-parallel extensional signal appears extremely stable all over the Western and Eastern Alps. Extensional tectonics is closely linked with transcurrent one and both regimes indicate orogen-parrallel orientation of the σ3 stress axes. The occurrence of brittle extensional structures displaying similar orientations of extension all over the Alps may suggest that extensional brittle structures are part of a late phase of collisional deformation, in which the propagation of the alpine front on the western Alps and the northward movement of the Southern alpine and the Adriactic indenters in the Central and Eastern Alps, were accommodated by orogen-parrallel extension in the inner zones, on the scale of the entire chain. The presence of free boundary may help lateral escape and the development of orogen-parallel extension that accommodate perpendicular-orogen shortening.

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Sequence of shortening in the Mont Blanc and Aiguilles Rouges massifs from thermal and thermochronological data

A. Boutoux[1]; N. Bellahsen[1]; U. Nanni[1]; J.B. Girault[1]; R. Pik[2]; A. Verlaguet[1]; Y. Rolland[3]; O. Lacombe[1]

1 Sorbonne Universités, UPMC Univ Paris 6 iSTeP 4 place Jussieu 75005 Paris, France Contact : alexandre.boutoux@upmc.fr

2 CRPG, Université de Lorraine, CNRS, 7358, F-54501 Vandoeuvre-Lès-Nancy, France.

3 Géoazur, Université de Nice Sophia-Antipolis, CNRS, UMR 7329, Valbonne, France.

Thermicity and kinematics of collisional wedges are key to understand crustal rheology during collision, especially in thick-skinned mountain belts, where deep crustal levels are exhumed. In the Western Alps, the large body of available data now allows a detailed study of both thermal and structural evolution.

In this contribution, from new (U-Th-Sm)/He data on zircon (ZHe) and new Raman Spectroscopy on Carbonaceous Material (RSCM) data on samples from the Aiguilles Rouges and Mont Blanc massifs (External Crystalline Massifs, Western Alps) and their cover, coupled to HeFTy thermal modeling, we constrain both the thermal structure and evolution of the Alpine collisional wedge.

Above the Aiguilles Rouges massif, RSCM data indicate that the peak temperature was about 315°C in the autochthonous cover. In the cover units located all around the Mont Blanc massif (i.e., the Morcles and the Mont Joly nappes, the Chamonix and the Courmayeur basins), maximal temperature reached are constant, around 350°C. Moreover, isotherm geometry, oblique to the nappe folds and probably dipping NW, strongly suggest that the Mont Blanc massif cover was deformed at the temperature peak and extruded from its basin during cooling of the massif. Finally, ZHe data coupled to thermochronological and geochronological data from literature point toward a coeval cooling and exhumation of both Aiguilles Rouges and Mont Blanc massifs both initiated at 16-18 Ma.

These results allow refining the evolution of both the thermal and the structural evolution of the external Western Alps. During an overall in-sequence propagation of the shortening, the Mont Blanc massif was shortened at thermal peak during Oligocene times (30-23 Ma). It is

noteworthy that this thermal peak lasted 10-15 Ma in the Mont Blanc massif, and possibly 5-10 Ma in the Aiguilles Rouges massif. At 23 Ma, the Mont Blanc Shear Zone was activated, yet allowing no significant cooling of the massif and its cover. At 16Ma, both cooling and exhumation are initiated, coevally with the activation of a crustal ramp below the Aiguilles Rouges massif. At this time the activity of both the Mont Blanc Back Thrust and the Mont Blanc Shear Zone suggest the widening of the underplating zone below the wedge. Moreover, during this period, the Chamonix basin is pinched leading its cover to be extruded northwestward above the Aiguilles Rouges massif. Finally, at 11 Ma, the Jura fold-and-thrust-belt is formed at the wedge front.
One of the major results of this contribution is that significant shortening recorded in the Mont Blanc massif is synchronous in the cover and the basement and is experienced during their thermal peak (lasting around 10 Ma at 300-400°C), before the onset of their exhumation.

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The art to reconstruct the evolution of HP-terrains using a petrochronological approach

Burn Marco, Kunz Barbara, Giuntoli Francesco, Lanari Pierre, Engi Martin

Inst. für Geologie, Univ . of Bern, Baltz 1-3, CH-3012 Bern, Switzerland

Deciphering the information stored in polymetamorphic units remains a major challenge in Alpine geology. In studying the pre-Permian rocks from the Sesia – Dent Blanche nappe and outliers (e.g. the Monte Emilius slice), we find that each sample may record various stages of the protracted PTt-evolution: A pre-Permian imprint, a Permian metamorphism of amphibolite to granulite facies, then one or more Alpine high-P stages acquired upon subduction/collision, and finally a retrograde stage at blueschist to greenschist facies conditions, reflecting exhumation. The aim is to quantify the history of such rocks, based on detailed petrographic analysis, including the identification of assemblages, relic minerals and signs of interaction with fluids. The result of these analyses is that samples, for which PTt-conditions of some metamorphic stage(s) can be reliably determined, are rare. Samples generally do not record peak metamorphic conditions but stages of mineral growth resulting from the breakdown of precursor assemblages. Hence, samples from the same lithology with a similar PTt-history may well record different PTt-points of their path, none of which correspond to 'peak metamorphic' conditions. This paradigm shift is crucial when interpreting metamorphic age data and trying to understand their significance.
This contribution focuses on the petrochronological approach we use in order to gain insight into details of this complex scenario by deciphering PTt-information from mono- and polycyclic units. Zircon growth zones have mainly been analyzed to understand the Permian history and the origin of old paragneiss (Kunz et al. 2015). Allanite proved particularly suitable in relating age data to different PT-stages of the Alpine history. To link allanite ages (mostly 208Pb/232Th) to the corresponding PT-conditions, various techniques are typically used. Optical observations of mineral textures and assemblages remain the cornerstone for specific microanalytical techniques, such as the study of tiny inclusion by Raman spectroscopy. Characterization of datable minerals and growth zones by BSE or CL imaging helps us select appropriate zones of datable minerals and associated phases. For PT-calculations quantitative X-ray mapping (Lanari et al. 2014) is increasingly used instead of arbitrary EMPA spot analyses, as the importance of local bulk is more and more recognized; finally, trace element and isotopic analysis for age dating is performed using the LA-ICP-MS facility at the University of Bern. In addition to phase diagram calculations, a variety of semi-quantitative thermobarometers and iterative forward modelling (Giuntoli et al. 2015) are used in order to estimate PT-conditions. A large number of well constrained PTt-data have been gathered in the course of this project, from pre-Permian to Alpine stages of the evolution. Dating and characterization of zircon from the Ivrea, Sesia, Dent Blanche and Monte Emilius units underscore the role of HT-protoliths in Alpine HP-rocks and give first insights into the actual relations of various Austroalpine units at Permian time. Detailed resolution of Alpine PTt-paths by allanite petrochronology reveals several stages of HP-metamorphism in the Sesia zone, between 85 and 60 Ma. Allanite from Glacier Rafray and Tour Ponton outliers give consistent HP-ages around 45 Ma, whereas first results of allanite in HP-metamorphic assemblages from the Monte Emilius outlier indicate a spread from 65–45 Ma. Taken together, these PTt-data provide a basis to analyze the evolution in the internal Western Alps, quantify the duration of various tectono-metamorphic stages of evolution, and derive rates for several processes.
The importance of recycling crustal material in collision zones is evident in the Western Alps and in similar orogens (e.g. Western Norway) that underwent a tectonic transition from pre-orogenic extension (rifting) to plate convergence, involving continental subduction, collision, and tectonic exhumation. Petrochronological analysis is an effective (but laborious!) method to decipher the archive of polycyclic rock samples and, when combined with structural analysis, contributes to a deeper understanding of geodynamically complex situations (e.g. Regis et al. 2014; Engi et al. 2015; Lanari et al. 2015; Verly et al. 2015).

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Geological inheritance and Alpine Tectonics: implications for the temporal evolution of orogens.

Butler, Rob

School of Geosciences, University of Aberdeen, UK.
rob.butler@abdn.ac.uk

Stratigraphic and structural studies in mountain belts, including the Alps, is revealing the structure of the former rifted continental margin and basins from which these belts have formed. The localisation of contractional structures during orogenesis can be strongly influenced by inherited heterogeneities. Within the continental crust such controls are most obvious when associated with reactivation by thrusts of earlier rift faults (tectonic inversion). However, other geological aspects exert controls, such as the distribution of basement heterogeneities, and fluid-related retrogression, in a similar fashion to layer-form rheological structure in the sedimentary cover influence "structural style" in fold-thrust belts. The distribution of basic intrusives in the continental crust will exert a fundamental influence on the evolution of buoyancy during deep burial and hence the propensity of the subduction of different continental tracts. Serpentinised crust-mantle contacts, inherited from hyperextended margins, can influence the depth and residence time of continental fragments in subduction channels that are manifest in complex records of UHP and HP metamorphism and exhumation – and generates complex patterns of coupling with evolving orogenic systems. In this regard, collision mountain belts are amplifications of inherited lithospheric heterogeneities.
But how do these heterogeneities amplify? If deformation is controlled by the preferential exploitation of weak zones and the distribution of buoyancy within converging lithosphere, the various controls will play at different places and times during the evolution of the orogeny. While the necessary kinematic tests of large-scale tectonic interpretations in the Western Alps and other orogens can be achieved through section balancing, the complexities in temporal evolution predicted in the introductory narrative here demand the integration of radiometric data and stratigraphy. To date these approaches commonly build from assumptions of pulsed, sporadic tectonic events. Both require reappraisal if we are to extract the temporal evolution of deformation patterns necessary to test tectonic models. Simple models of outward migration of deformation through time are unlikely to apply. While polyphase deformation is a standard expectation for investigations of the once deeply-buried parts of orogens, in general they are not for the external zones. If viewed locally, complex deformation histories might appear to record distinct, regionally significant phases but are most plausibly part of a temporal continuum that is expressed heterogeneously in space.
To illustrate these issues examples will be drawn from the Western Alps, specifically along the Grenoble-Briancon-Turin transect. External zone tectonics and the debate on the significance of pre- vs post-Nummulitic deformation can be resolved in a continuum model – with sand fairways along the Eo-Oligocene turbidite systems forming a key spirit-level and denudation guide for outer Alpine structural evolution. They may also provide significant constraint on deformation further into the orogen.

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Mechanical analysis of the thin- versus thick-skin current tectonics in the Jura thrust belt (Swiss Alps)

Caër Typhaine[1], Maillot Bertrand[1], Souloumiac Pauline[1], Leturmy Pascale[1], Nussbaum Christophe[2]

1 Dept Géosciences et Environnement, Université de Cergy-Pontoise.
2 Federal Office of Topography swisstopo, Wabern, Switzerland
typhaine.caer@u-cergy.fr

The Jura is a typical thin-skin fold-and-thrust belt developed over a triassic decollement. However, the current style of deformation in the folded Jura is a recurrent question as seismological studies do not allow to conclude on this question. In order to determine the behavior of the current deformation, we used the mechanical theory of the Limit Analysis to test geological sections across the Jura considering the competition between the Triassic decollement and the mid-crustal decollement. We show that the oriental end of the folded Jura undergoes thick-skin tectonics whatever the friction values on the different decollements, with, in some cases, a simultaneous activation of the Triassic decollement. Southward, along the ECORS profile, the folded Jura is undergoing thin-skin tectonics, because depending on friction values, deformation on the mid-crustal decollement is either limited to the Molasse Basin, or propagates outward well beyond the Bresse graben, a geologically unrealistic scenario. In between, we show that the mid-crustal decollement may be activated under the folded Jura. These results show that there is a limit in the Jura between a thin-skin area and a thick-skin area which position depends on the friction angle that we consider on the two main decollements.

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Imaging the deep architecture of mountain ranges: A review of recent results obtained in the Pyrenees

Chevrot, Sébastien

CNRS, GET, Observatoire Midi-Pyrénées, 14 Avenue Edouard Belin, 31400 Toulouse. sebastien.chevrot@get.obs-mip.fr

The recent PYROPE and IBERARRAY deployments have considerably increased our capacity to image the deep architecture of the Pyrenees. The exploitation of this rich dataset is still in progress. We will review the first important results that were already obtained using classical tomographic approaches such as regional travel time tomography, receiver functions migration or ambient noise tomography. We will discuss the limitations of these classical approaches and identify the main challenges that seismologists have to face when working in such complicated environments as mountain ranges. We will then introduce a new imaging approach based upon full waveform inversion of short period teleseismic waves. This approach allows us to obtain sections of both compressional and shear velocities at the scale of the lithosphere and with a very fine resolution (kilometric). It is particularly well adapted to handling data from dense transects. We will show the models obtained with this waveform inversion method using several teleseismic P waves recorded along a dense transect across the western Pyrenees. These new tomographic images reveal crustal and lithospheric structures with unprecedented resolution and bring crucial informations on the structure and evolution of the Pyrenees.

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Quaternary sediments as a tool for seismotectonic evaluation of the Culoz, Col du Chat and Vuache fault, Southern Jura - Western Alps - Implications for the seismic hazard.

De La Taille, C.[1,2], Jouanne, F.[1], Jomard, H.[2], Beck, C.[1], Crouzet, C.[1]

(1) Univ de Savoie Mont Blanc, ISTerre, CNRS, 73376 Le Bourget-du-Lac, France. delataic@univ-savoie.fr
(2) IRSN BERSSIN, 92260 Fontenay-aux-Roses, France

In the southern Jura, the Vuache, Culoz and Col du Chat left lateral strike-slip faults compensate the difference in tectonic prism at low coefficient of friction basal north and intensive basal friction in south. Nevertheless clues suggest crustal roots of these faults. This work is a contribution to a better understanding of active faults at the junction Jura - Alps. The Vuache fault is ending to the SE in the Lake Annecy, the Culoz and Col du Chat faults are ending in the Bourget Lake. The objective of this work is to study the geometry of the three left-lateral strike-slip faults in the Southern Jura to force its seismic potential. For that several methods were used: historical and paleoseisms, very high resolution seismic reflection in the lake of Annecy and the Bourget lake, electrical resistivity tomography and industrial seismic reprocessed by BRGM. These faults have a long time recurrence (over a thousand years), marked by historical seismicity. Therefore, a specific approach to characterize the seismic activity of faults is employed rather than an analysis limited to the historical catalog. This is especially necessary in France as part of the evaluation of the seismic hazard for sensitive and classified facilities (nuclear power plants, dams, etc ...). In the study area, most markers Pliocene-Pleistocene deformation have been eroded by successive glaciations. Therefore, the markers may have recorded the deformation are generally recent sediments as post-Würmian lakes. High resolution seismic have allowed to image the quaternary filling of the lake, and to locate and quantify the deformation. The different profiles show that Holocene sediments are affected by deformations. Seismic profiles acquired in Lake Le Bourget allow to image a system of Riedel faults in the quaternary infill of the lake and a well localized fault in the Mesozoic basement corresponding at the Culoz fault. The observation of faulted quaternary sediments onshore and in the continuity of this fault reinforces our interpretation. High resolution seismic profiles performed in the Annecy Lake allow imaging a “ponytail” termination of the Vuache Fault, termination characteristic of strike-slip faults. The CLIMASILAC project permits to have a carrot of Annecy Lake. The carrot showed a relative abundance of gravity reworking during the Late Glacial, but also their synchronization with the highest sedimentation rate. A greater number of disturbances interpreted as sismites are present at the base of the core, there is then probably more earthquakes recorded at the base. This would mean that following or during deglaciation, the seismic activities was greater than now, so this would tend to favor a contribution of déflexuration in the forces controlling the current deformation. Industrial seismic profiles allow establishing that Culoz and Vuache are rooted in the basement. Moreover, the instrumental seismicity of the Vuache fault is shifted of 1.5 km to the NE by comparison to the fault trace, like the basement fault. We can then suggest that the Vuache Fault is separated in two branches, a northern one shifted of 1.5 km to the NE by comparison of the southern one corresponding at the geological fault trace. Taking into account (1) the length of these faults (25 to 40 km for Culoz fault, 12 to 41 km for Vuache fault) and (2) the depth of recorded earthquakes (between 4 and 14 km for Culoz Fault and between 4 and 21 km for the Vuache fault), the potentially ruptured surface could range from 100 to 600km². The latter implies a Moment Magnitude range from M6.0 to M6.8 for the Culoz fault, for the Vuache fault: M6.3 to M6.7 based on worldwide empirical scaling relationships (Wells & Coppersmith 1994).

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Architecture of the the Piedmont-Ligurian rifted margins: hints for a flip of the rift system polarity

Decarlis Alessandro[1], Manatschal Gianreto[1] & Beltrando Marco[2]

1 EOST/IPGS Universitè de Strasbourg, Rue Blessig, 1, F-67084 Strasbourg Cedex (F), decarlis@unistra.fr; manat@unistra.fr
2 Dipartimento di Scienze della Terra Università degli Studi di Torino, Via Valperga Caluso, 35, 10125 Torino (I), marco.beltrando@unito.it

Research on processes and dynamics of magma-poor rifted margins strongly developed in the last decade. Since exhumation of sub-continental mantle along extensional detachment faults has been demonstrated in both modern and fossil examples, the knowledge on the distal parts of rifted margins strongly progressed. The first-order characters on the architecture and evolution of magma-poor rifted margins have been suggested by Sutra et al. 2013 and Tugend et al. 2014. These authors developed a general framework to approach the geometry on different margins integrating the knowledge on the proximal and distal part of the rifted system. In addition, they defined the elements which characterize the upper and lower plate of the rifted system. This concepts, together with the sedimentary architecture of the different rift basins (i.e. Masini et al. 2014), represent a powerful tool to decipher the whole structure of most of the magma-poor margins. In this context the Alps represent a key area where sediments and primary rift structures can be observed and compared with the seismic and drill hole data from present-day margins. In this study we apply these concept to two type-sections across the Alpine rifted margins that are currently located on either sides of the Periadriatic line: the Ligurian Briançonnais and the Southalpine margin. The analysis of their well-known pre-, syn- and post-rift stratigraphic record (e.g. Decarlis et al. subm.; Berra et al. 2008) allows the recognition of the main key-areas, i.e. the proximal and distal domain separated by necking zones and the exhumed domain. Furthermore, the Ivrea-Verbano zone in the Southalpine section offers a unique look to the deeper part of the continental crust (Brack et al. 2010), which elements have been integrated in our interpretation. From this first-order analysis we recognized a similar architecture for the two sections that is consistent with a typical upper plate margin. This view differs from the previous interpretations, where the studied margins were considered as coupled (i.e Briançonnais as upper plate and Southalpine as lower plate) and possibly even directly conjugates. In our interpretation the Briançonnais and the Southalpine are coevally developed margins, which rest respectively North and South of a major transform zone (at present roughly represented by the Periadriatic line) that accommodate a flip in the polarity of the rift system during Middle Jurassic. This interpretation leads to important implications for the overall structure of the Jurassic Alpine rifting but also for the significance of the main tectonic structures of the Alps and for their paleogeographic evolution, opening new question about the role of rifting-related inheritance of the late compressional structures inside orogens.

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Revisiting the Bracco-Levanto ophiolite: 46 years after the pioneering idea of mantle exhumation by detachment faulting

Decarlis Alessandro[1], Tribuzio Riccardo[2], Picotti Vincenzo[3], Manatschal Gianreto[1], Gillard Morgane[1], Bonzani Andrea[2], Sbaffi Mattia[2] & Stelitano Matteo[2]

1 EOST/IPGS Universitè de Strasbourg, Rue Blessig, 1, F-67084 Strasbourg Cedex (F), decarlis@unistra.fr;
2 Dipartimento di Scienze della Terra e dell'Ambiente, Università degli Studi di Pavia, Via Ferrata, 9, 27100 Pavia
3 ETH Zürich-Geologisches Institut, Sonneggstrasse, 5, 8092 Zürich

The Bracco-Levanto ophiolite belongs to the Internal Ligurian units of the Northern Apennine. This ophiolite consists of a basalt-sedimentary succession of Jurassic age directly lying on top of a gabbro-mantle association. Since the late 60s, the Bracco-Levanto ophiolite was analysed in great detail to study the local geology and to understand the processes associated with the formation and evolution of the oceanic crust (Tribuzio et al., 2014, and references therein). Decandia and Elter (1969) proposed the pioneering idea of low-angle sub-continental detachment faults to explain the exhumation of the mantle sequence of the Bracco-Levanto ophiolite. With their interpretation, they anticipated the later discovery of exhumed mantle along the Iberia margin, where extensional detachment faults where seismically imaged and drilled during ODP Leg 103 (Boillot et al. 1987). Revisiting the "classic exposures" with some of the new ideas and concepts developed in the last 46 years enables to re-map and re-interpret the contacts between the gabbro-mantle basement and the basalt-sedimentary cover, as well as some of the deformation structures. In this study, we present a new map and some new observations of the southeast of the Bracco-Levanto area, between Framura and Levanto. Here the exhumed mantle is formed by a suite of serpentinized peridotites intruded by different gabbro bodies (cfr. Cortesogno et al. 1987). At their top, ophicalcites associated with tectonic and sedimentary breccias mark the occurrence of the extensional detachment surface. The latter was successively covered by a thin discontinuous layer of siliceous sediments followed by a ~400 m thick succession of massive basalts exposed SE of the Bonassola village. This succession displays evidence for greenschist facies shear zones at the base, thereby showing emplacement under an active tectonic regime. The massive basalts are interleaved with thick bodies (up to 10 m) of reworked siliceous sediments. Basalts pass to a breccia body composed of mafic clasts derived from the substratum and west of Bonassola village to a thick succession of pillow basalts directly lying on top of the detachment surface. We interpreted this succession as influenced by the activity of a SE-dipping Jurassic normal fault that dissected the original extensional detachment and that lies at present buried under the volcanics and younger sediments (Pillow basalts, Diaspri di Monte Alpe and Argille a Palombini). These observations are similar to those evidenced in seismic sections along the Antarctica margin (GA228-27; Gillard 2014), where similar high-angle structures cut the extensional detachment fault in the most distal part of the "proto oceanic" corridor and where the exhumed mantle approaches the oceanic domain.

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Structure and restoration of the Briançonnais zone : a reappraisal of the early Alpine deformation episodes

Thierry Dumont[1], Aude Verly[1], Pierre Lanari[2], Stephen Matthews[3]

1 ISTerre CNRS, Univ. Grenoble Alpes, 1381 rue de la Piscine, 38041 Grenoble cedex 9, France. thierry.dumont@ujf-grenoble.fr
2 Institute of Geological Sciences, University of Bern, Switzerland
3 Frontier Structure Limited, Oxfordshire, OX394RZ, UK

The pre-collision restoration of the Briançonnais domain in the Western Alps is closely dependent on the knowledge of the Alpine kinematics and of the structure of the Internal zones. Field investigations along the Durance, Guil and Ubaye valleys, crossing perpendicularly the Briançonnais zone from the central to southern part of the arc, together with the help of geological maps draped over a digital elevation model, allow examination of the early shortening and nappe stacking phases. Several sites show (a) top-to-the north or northwest (orogen-parallel) tectonic transport criteria, which are overprinted by further (b) orogen-perpendicular shortening, either westward to southwestward stacking linked with the activity of the «penninic thrust» to the west, or backfolding and backthrusting along the eastern boundary of the Briançonnais zone.

The early (a), N-NW directed episode is recorded on both sides of the Briançonnais zone, in the footwall of the Embrunais-Ubaye nappes to the west (Dumont et al., 2011) and in the oceanic Schistes Lustrés nappes stack to the east (Tricart & Schwartz, 2006). It corresponds to Eocene continental subduction directly driven by the Adria-Europe convergence, and it is likely responsible for large distance nappe transport. The Oligocene (b) kinematics were driven by extrusion and involved the mixed, oceanic and continental accretionary wedge developed during the previous stage which was rapidly exhumed and tilted. Consequently, the initial nappe stack was reshaped and distorted to produce the most prominent structures which delinate the internal arc.

In the study area, this post-nappe deformation consists of outerward thrusting involving the whole stack and cross-cutting of the previous sole thrust ("Penninic thrust" cross-cutting the Embrunais- Ubaye thrust), innerward fold-and-thrusting (the well-known backward deformation along the eastern Briançonnais zone), and counterclockwise rotations, which are increasingly important southwards (Collombet et al., 2002). Our cross-sections indicate that backfolding has considerably altered the initial structure of the nappes, possibly in association with large scale backthrusts at depth, therefore requiring careful description of the present geometry to allow assessment of models for the pre-alpine setting. The high-amplitude backward deformation observed near the surface, which was probably triggered by the westward indentation of the Ivrea body at depth, as suggested by recent geophysical data, must be restored carefully to allow production of viable paleogeographic reconstructions. A comparison of the three cross-sections with the post-nappe deformations removed, suggests initial north to northwest directed nappe transport, which is corroborated by the microstructural evidence for top-to-the north to northwest tectonic transport. Thus the paleogeographic origin of the Briançonnais nappes which are involved in the Western Alpine arc is considered probably to the southeast, and not in the core of the arc. Consistently, the thick late Carboniferous units found in the Briançon area, and further north, are probably derived from late Hercynian basins which have experienced compression and uplift (possibly through localised basin inversion) initially located in the southern foreland of the Variscan chain (von Raumer et al., 2012). The early Alpine nappe stacking occurred before the Eocene-Oligocene boundary as shown by new geochronological data acquired both in one inner Briançonnais unit (Acceglio-Longet unit) and in the adjacent oceanic unit (Verly et al., this volume).

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Impact of pre-rift inheritance on Jurassic rifting in the Alps: insights from lithospheric models

Thibault Duretz, Geoffroy Mohn, Stefan Schmalholz

University of Lausanne, thibault.duretz@unil.ch

The Alpine orogen consists in rock units that underwent a polyphase geological history. The events that pre-date Alpine collision include (1) Permian post-orogenic extension and (2) Jurassic rifting events. The post-Variscan orogenic extension is marked by the intrusion of magmatic bodies within the continental basement and a widespread magmatic underplating event. Permian post-orogenic extension was thus responsible for pre-structuring the crust prior to Jurassic rifting. Pre-rift structural and thermal inheritance thus plays a key role in the development of Liguro-Piemontese and Valaisan domains. We developed two-dimensional thermo-mechanical models of lithospheric extension to study the role of pre-rift inheritance on the development of rifted margins. We highlight the role of lithospheric mechanical layering that allows for multi-stage depth-dependent extension. During the first stage of rifting, lithospheric deformation is decoupled: the crust is thinned by brittle (frictional-plastic) faults and the mantle is subjected to symmetric ductile necking. However in the second stage, low angle extensional shear zones develop across the lithosphere leading to asymmetric extension. This coupled deformation phase allows for the coeval formation of crustal allochtons and adjacent basins. We describe the first-order geometrical and thermal evolution predicted by the numerical models and discuss our results in the context of the Alpine geological history.

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Metamorphic and structural evolution in the internal Western Alps

Engi Martin[1], Giuntoli Francesco[1], Burn Marco[1], Kunz Barbara[1], von Niederhäusern Brigitte[1], Lanari Pierre[1], Robyr Martin[1], Manzotti Paola[2], Regis Daniele[1], Rubatto Daniela[1,3], Darling James[4], Cenki-Tok Bénédicte[5], Compagnoni Roberto[6]

1 Dept. of Geological Sciences, University of Bern, Baltzerstrasse 1-3, CH-3012 Bern; (engi@geo.unibe.ch) ;
2 Géosciences Rennes, Université de Rennes1, F-35042 Rennes;
3 Research School of Earth Sciences, Australian National Univ.
4 School of Earth & Environmental Sciences, Portsmouth PO1 3QL,
5 Géosciences Montpellier, Univ. de Montpellier, F-34095 Montpellier;
6 Dept. of Earth Sciences, Univ. of Torino, I-10125 Torino.

The internal Western Alps host several classic high-pressure terranes, such as the Sesia Zone (SeZ) in northern Italy. At the SE margin of this zone, the Alpine eclogite facies metamorphism is truncated by the Insubric line, which separates it from Ivrea Zone with only weak Alpine imprint. Recent efforts have focused on the PTt-evolution and internal structure of the SeZ and of continental units located to the NW, on top of ophiolite units of the Piemont-Liguria domain. The main advances made were based on detailed mapping, structural analysis, and petrochronology, i.e. dating specific stages of the metamorphic evolution.

Essential new evidence of the tectonic situation has been gained from studying monocyclic metasediments with Mesozoic protoliths. Although poly-deformed, these metasediments (marbles, quartzites and schists) delimit units of polycyclic gneiss and schist. Their role is best understood in the Dent Blanche complex, mostly within the Roisan-Cignana Shear Zone, and similarly in the Pillonet klippe (Manzotti et al. 2014a,b). In the SeZ the monocyclic metasediments principally occur as tectonically reduced trails, but when mapped in conjunction with high-strain zones, they aid in delimiting km-thick sheets and hectometric slices (Giuntoli et al. 2015a) that make up two main complexes: The Internal Complex (IC) comprises several subunits of eclogitic micaschist and orthogneiss (of Permian and older protoliths); in the External Complex (EC) three sheets of gneiss (“minuti”) and two separate sets of 2DK-boudins are interleaved. A shear zone with two major slices of high-strain metasediments separate the IC from the EC, at 40-50° discordance. To check if further tectonic slices exist outside the central Sesia Zone, high resolution mapping needs to be extended, and detailed structural analyses of the metamorphic imprint (e.g. Zucali & Spalla, 2011) require age dating.

Attempts to reconstruct the assembly of the internal Western Alps hinge on linking reliable PT-paths to age data from the main units. Recent in situ petrochronology applied to well characterized HP-assemblages has yielded robust (U-Th-Pb) age data that trace for the first time several PTt-stages for individual samples. Regis et al. (2014) reported a gradient within the IC, with HP-ages ranging from ~86 Ma (for Pmax~2 GPa at 550 °C) in the internal part, to ~75 Ma (for Pmax~1.8 GPa at 530 °C) in a central part of the SeZ. Rubatto et al. (2011) reported evidence of tectonic cycling (“yo-yo”): a second HP-peak (Pmax~1.7 GPa at 550 °C) was reached at ~65 Ma, after intermittent cooling and decompression to blueschist facies. Giuntoli et al. (2015b) has found similar P- but higher T-conditions (~620°C) in another sheet of the central SeZ, but with zircon and allanite ages there being <70 Ma. Conditions in the most external non-eclogitic parts of the SeZ and in several eclogitic klippen units are still being refined (Burn et al. 2015).

Apart from addressing the convergent history, recent work has focused on the pre-Cretaceous evolution. At least some of the Mn-metacherts in the Dent Blanche are pre-Jurassic basement (Manzotti et al. 2012). The extent and age of regional Permian HT-metamorphism is now clear; post-Variscan heating is evident in all of the continental basement units examined (SeZ, Dent Blanche, and external klippen). PT-conditions and ages show many similarities with the Ivrea Zone (Kunz et al. 2015). Repeated influx of fluid is evident in some samples of eclogitic micaschist from the central SeZ – the dominant rock type in this area – with relic cores of Permian HT-garnet being partly replaced (forming atolls) and then rimmed by HP-garnet. Growth zones in previously dry metapelites (kinzigites) indicate two stages of rehydration at eclogite facies, during heating and subduction (I: 650°C, 1.5 GPa: II: 670°C 1.7-2.0 GPa; Giuntoli et al. 2015b). During retrogression in (notably highly strained) parts of the SeZ, hydration must have continued, again leading to stages of garnet resorption and growth (Konrad-Schmolke et al. 2006). The formation of the typical eclogitic micaschists in the SeZ and some external klippen units is thus attributed to reactive fluids circulating within the subduction channel, which favored eclogitization of previously dehydrated Permian granulites and mafic intrusives.

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Characterization of extensional detachment systems in hyper-extended domains: examples from the Err nappe (SE Switzerland) and Prepiémontais units (SE France).

Marie-Eva Epin, Gianreto Manatschal, Isabelle Haupert, Alessandro Decarlis

IPGS, EOST-CNRS, Université de Strasbourg, 1 rue Blessig, F-67084 Strasbourg Cedex, France, meepin@unistra.fr

Despite of the fact that many studies investigated magma-poor rifted margins, there are still open questions that are related to the nature of basement topography and the timing and processes related to their formation. While these questions are difficult to answer at present-day margins due to the lack of drill hole data, field analogues provide important insights and enable to find some answers to these questions. This is particularly true for the Err nappe in southeastern Switzerland, which is one of the world's few exposed and preserved rift-related hyper-extended domains. This nappe preserves a rift related extensional detachment system that is exposed over more than 200km2, characterized by distinctive black gouges, green cataclasites and preserving the relation to its hanging wall and footwall rocks and the pre-, syn-, and post-tectonic sediments. Similar structures, but much more overprinted by the Alpine reactivation, are also exposed at the conjugate most distal margin within the Prepiémontais units in the Western Alps.

In the example of the Err nappe the 3D architecture of the rift related detachment system can be mapped in detail. The detail mapping shows the lateral variation of the morphology of the major detachment fault and its relation to extensional allochthons and the pre-, syn- and post-tectonic sediments. The main observation is that the architecture of the detachment system changes over very short distance from an extensional detachment fault that is overlain by allochthonous blocks (e.g. Bardella block), to an area where the same fault is exhumed at the seafloor, overlain by tectono-sedimentary breccias, and sealed by post-rift sediments. The mapping of the syn-tectonic sediments shows strong variations in thickness and facies. Some facies including reworking of hanging wall and footwall derived material are interleaved with either turbidites or pelagic deep marine sediments forming the background sedimentation. Furthermore there is evidence for intense fluid and reaction assisted brittle deformation resulting in characteristic fault rocks that can be found locally reworked in the syn-tectonic sediments. These relationships suggest a rapid change from a domain where the extensional detachment is overlain by allochthons and thick syn-tectonic sediments to a domain where the detachment is exposed at the sea floor.

Although more overprinted by the Alpine convergence, outcrops in the Prepiémontais units (former internal Briançonnais domain of Lemoine [1961]) show similar relationships like those reported from the Err nappe. In the Prorel and Rio Secco-Grand Chalvet units, remnants of syn-tectonic sediments with basement clasts, and extremely deformed and chloritized basement can be found, reminiscent of what can be seen in the Err nappe. It is interesting to note that these units are juxtaposed by thick, not continuous and little deformed Triassic dolomites overlain by syn-tectonic sediments. Since these units are interleaved tectonically with the previous one, they are difficult to explain by Alpine deformation only. However, the reworking of chloritized cataclasites and gouges within sedimentary syn-tectonic breccias suggest that the juxtaposition of these unit had to occur during deposition of the breccias prior to Alpine collision. Thus, these areas may result from the reactivation of rift-related structures similar to those described from the Err nappe.

In our presentation we will present the field relationships and will discuss the tectonic processes and implications, as well as the timing of these structures and their role during subsequent Alpine reactivation.

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Mountain building and mantle dynamics

Claudio Faccenna[1], Thorsten W. Becker[2], Clint Conrad[3] and Laurent Husson[4]

1 LET, Laboratory of Experimental Tectonics, Università Roma Tre, Rome, Italy (faccenna@uniroma3.it)
2 Department of Earth Sciences, University Southern California, Los Angeles CA 90089, USA (twb@usc,edu)
3Department of Geology and Geophysics, SOEST, University of Hawaii, Honolulu, HI 96822, USA (clintc@hawaii.edu)
4CNRS UMR 6118, Géosciences Rennes, Université Rennes 1, France (laurent.husson@univ-rennes1.fr) and CNRS UMR 6112, Laboratoire de Planétologie et Géodynamique de Nantes, France

Mountain building at convergent margins requires tectonic forces that can overcome frictional resistance along large-scale thrust faults, and that can support gravitational potential energy stored within the thickened crust once the orogen has formed. A general, dynamic model for this process is still lacking. Here, we suggest that mountain belts can be classified between two end-members.
Firstly, those of "slab pull" type, where subduction is mainly confined to the upper mantle, and rollback trench motions lead to moderately thick crustal stacks, such as in the Mediterranean.
Secondly, those of "slab suction" type, where whole mantle convection cells ("conveyor belts") lead to the more extreme expressions of orogeny, such as the large thickness crust and high plateaux of present-day Tibet and the Altiplano. The slab suction type of deep mantle convection produces the unique conditions to drag plates toward each other irrespective of their nature and other boundary conditions.
We support our arguments by analyzing the convective, orogenic, and volcanic history associated with the formation of the Andes and Himalayas. The formation of these orgenic belt started in the Tertiary, the Himalaya after collision around ~55 and the Central Andes slightly after around ~40. Based on mantle circulation modeling and tectonic reconstructions, we speculate that the forces necessary to sustain slab suction mountain building in those orogens derive, after transient slab ponding, from the mantle drag induced upon the penetration of slabs into the lower mantle, and an associated surge of mantle upwelling beneath Africa.
This process started first at ~ 65-55 Ma for Tibet, when the Tethyan slab penetrated the lower mantle, and later at ~ 50-40 Ma for the Antiplano, when the Nazca slab did. This vigorous surge of mantle convection drag plates one against each other, generating the necessary protracted compressional stresses to sustain orogen, generating the Himnalayan-Tibetan belt and the Andes, both from ~50-40 Ma onward. If our model is correct, the geological record of orogeny can be used to decipher time-dependent mantle convection, with implications for plate tectonic heat transport and the super-continental cycle.

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Interplay of extensional deformations and rotations within a few million years interval: an integrated paleomagnetic and structural study (Pohorje Mts. – Mura Basin, Slovenia)

Fodor, László[1], Márton, Emő[2], Vrabec, Marko[3], Jelen, Bogomir[4], Koroknai, Balázs[5], Rifelj, Helena[4], Trajanova, Mirka[4], Vrabec, Mirjam[3]

1- 1117 Budapest Pázmány P. 1/c, Hungary, MTA-ELTE Geological, Geophysical and Space Science Research Group of the Hungarian Academy of Sciences at Eötvös Loránd University, Hungary, lasz.fodor@yahoo.com
2- Geological and Geophysical Institute of Hungary, Palaeomagnetic Laboratory, Hungary
3- Dept. of Geol Univ. of Ljubljana, Aškerčeva cesta 12, 1000 Ljubljana, Slovenia
4- Geozavod Slovenia, Ljubljana, Slovenia
5- Geomega Ltd. Budapest, Hungary

We reconstructed the deformation history of the Pohorje pluton, related subvolcanic rocks and surrounding sediments in NE Slovenia. Methods involved classical field structural measurements, microtectonic observations in thin sections and different approaches of paleomagnetism. Particularly, we compared the main directions of deformation and the main axis of the anisotropy of magnetic susceptibility (AMS). We extended and reinterpreted our existing data base of Márton et al. (2006).
The granodioritic-tonalitic Pohorje pluton suffered crystal plastic deformation in the greenschist-facies, which is recorded by both AMS and microfabric characteristics. The deformation shows varying style within the pluton; extensional in the south and strike-slip type in the northern parts, respectively. Sub-horizontal (S) and steep foliation (N) is well developed, while associated with ENE–WSW (S) and SSE–NNW (N) lineation groups are recorded by stretched minerals and K1 AMS axis. This deformation occurred just after intrusion at 18.6 Ma (Fodor et al. 2008), during the imminent cooling of the plutonic rocks (18.6–18.4 Ma).
After this phase, at ca. 18.4–17.5 Ma, the pluton was intruded by andesite, dacite and aplite dykes. The AMS indicate ca. E–W minor extension, which is sub-perpendicular to the dykes themselves. During and after this event, the pluton underwent ca. 70°-80° clockwise rotation. After this rotation, at the end of Early Miocene (17.5–16 Ma) the just deposited cover sediments suffered incipient ductile extensional deformation, still at horizontal position. The NE–SW extension was recorded by AMS, and also by pre-tilt normal faults which are associated with mesoscopically continuous fault-related folding. This was followed by 25-45° CCW rotation.

This work was supported by the Hungarian Scientific Research Fund (OTKA) project no. K105245, 113013, and several bilateral Slovenian-Hungarian scientific cooperation projects.

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Structural evolution of the East Alpine-Pannonian junction area: from nappe stacking to extension

Fodor, László[1], Vrabec, Marko[2], Héja, Gábor[1], Jelen, Bogomir[4], Koroknai, Balázs[3], Németh, András[5], Rifelj, Helena[4], Trajanova, Mirka[4]

1 1117 Budapest Pázmány P. 1/c, Hungary, MTA-ELTE Geological Geophysical and Space Science Research Group, lasz.fodor@yahoo.com
2 Department of Geology, University of Ljubljana, Slovenia
3 Geomega Ltd. Budapest, Hungary
4 Geozavod Slovenia, Ljubljana, Slovenia
5 MOL Ltd., Hungary

The western part of the Miocene Pannonian Basin covers the transition from the Eastern Alps to the Pre-Miocene units composing the Pannonian Basin basement. Structural evolution of this area was reconstructed from surface observations, borehole data, seismic reflection profiles and 3D seismic data sets. Fault-slip and geochronological data were collected at the Miocene basin margins, in the Pohorje-Kozjak Mts. (Slovenia) and in the Transdanubian Range (TR) in Hungary.
The area is characterised by Cretaceous nappe stacking and internal folding and thrusting (Tari 1994). In the highest TR unit this deformation occurred before the Mid-Albian (before 108 Ma) while geochronological data scatter from 116 to 95 Ma in the underlying low-grade to medium grade unit (Árkai & Balogh 1989, Thöni 2002). The mid-Cretaceous thrust contact was reactivated or deformed by two phases of extensional deformation: few cooling ages indicate late Cretaceous exhumation of medium-grade Koralpe-Wölz metamorphics in the Kozjak Mts. (Fodor et al. 2003, 2008). Major structures are a wide mylonitic belt, shear bands, folds related to low-angle normal shearing, and in map-scale, extensional allochtons: they are composed of Palaeozoic rocks and the non-metamorphic Triassic sequence of the TR. This extensional deformation might have been connected to Senonian (Santonian to Campanian) basin formation in the hanging wall units (TR).
Good parts of the geochronological data set indicate Miocene cooling of the Koralpe-Wölz rocks and the Miocene Pohorje pluton. The Miocene exhumation resulted in low-angle detachment faults or mylonitic shear zones, a series of half grabens and few strike-slip faults playing as transfer faults. Tectonic exhumation resulted in the formation of metamorphic core complexes, like the Pohorje, Murska Sobota high and the Rechnitz windows of Penninic origin (Tari 1994, Dunkl & Demény 1997, Fodor et al. 2003). Extension affected the 18.6 Ma old Pohorje intrusion during its cooling through greenschist facies conditions between 18–15 Ma. Extension in the pluton was recorded by AMS data, crystal plastic and brittle deformation structures including Miocene magmatic dykes of variable composition (see also Fodor et al. this volume). This extensional deformation was connected to the opening of the Pannonian Basin from ca 18.5 Ma.
This work was supported by the Hungarian Scientific Research Fund (OTKA) project no. 113013, and several bilateral Slovenian-Hungarian scientific cooperation projects.

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Garnet growth and resorption records the PT-path from dry Permian granulite to Alpine eclogite facies rocks, involving HP-hydration in the Sesia Zone (NW Alps)

Giuntoli Francesco; Lanari Pierre; Kunz Barbara; Burn Marco; Engi Martin

Institut für Geologie, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland (francesco.giuntoli@geo.unibe.ch)

The extent to which granulites are transformed to eclogites is thought to impose critical limits on the subduction of continental crust. Although it is seldom possible to document such densification processes in detail, the transformation is believed to depend on fluid availability and deformation.
Remarkably complex garnet porphyroblasts are widespread in eclogite facies micaschists in central parts of the Sesia Zone (Western Italian Alps). They occur in polydeformed samples in assemblages involving phengite+quartz+rutile ±paragonite, Na-amphibole, Na-pyroxene, chloritoid. Detailed study of textural and compositional types reveals a rich inventory of growth

and partial resorption zones in garnet. These reflect several stages of the polycyclic metamorphic evolution. A most critical observation is that the relic garnet cores indicate growth at 800 °C and 0.75 GPa. They occur repeatedly in eastern parts of the Internal Complex (mapped by Giuntoli et al.; this conference) and are derived from granulite facies metapelites of Permian age. These dry protoliths thus must have been extensively hydrated during Cretaceous subduction, and garnet records the conditions of these processes.
Garnet from micaschist containing rutile, epidote, paragonite and phengite were investigated in detail. Two types of garnet crystals are found in many thin sections: mm-size porphyroclasts and smaller atoll garnets, some 100 µm in diameter. X-ray maps of the porphyroclasts show complex zoning in garnet: a late Paleozoic HT-LP porphyroclastic core is overgrown by several layers of HP-LT Alpine garnet, these show evidence of growth at the expense of earlier garnet generations. Textures indicate three stages of resorption, with garnet cores being fractured and then sealed by garnet veins, rimmed by multiple Alpine overgrowth rims with lobate edges.
Garnet rim 1 forms peninsula and embayment structures at the expense of the core. Rim 2 surrounds rim 1, both internally and externally, and seems to have grown mainly at the expense of the core. Rim 3 grew mainly at the expense of earlier Alpine rims. In the same samples that show porphyroclastic garnet, atoll garnet occurs, filled with quartz and rarely phengite, and the same Alpine overgrowth zones are observed in both types of garnet. Similar features of garnet zoning are present in various lithotypes, allowing the evolution of this continental domain during subduction to be traced.
Modeling garnet growth zones is challenging, as each growth step demands an estimate of the effective bulk composition. According to the XRF analysis of the bulk sample, the core is found to have formed at 800°C, 0.75 GPa. Based on effective bulk compositions, the successive Alpine rims are found to reflect an increase from ~650°C, 1.5 GPa for rim 1 to ~670°C, 1.7-2.0 GPa for rim 2 and rim 3. Allanite crystals contain inclusions of Alpine garnet, phengite and rutile; in situ geochronology (U-Th-Pb by LA-ICP-MS) on allanite yields a (minimum) age of ~69 Ma for the main growth of Alpine garnet rims. Zircon in these eclogitic micaschists shows partial resorption and new growth at 68-57 Ma as well as 310-250 Ma. Comparable metapelitic granulites with Permian mafic intrusives occur in parts of the Ivrea Zone.
The oxygen isotopic composition of quartz from different structural domains has been analyzed by SIMS (Cameca-1280). In the two samples analyzed, each growth domain shows uniform d18O values (±0.1 ‰), but variations overall show a range from ~13.5 to 15.1 ‰. Differences correlate with petrographically identified growth generations. Detailed profiles across quartz grains indicate no major diffusion effects. Late quartz (e.g. in cores of atoll garnet) indicate a systematic trend towards d18O ~14.5 ‰ (from higher d18O in sample A, from lower d18O in sample B). This suggests growth from a reactive hydrous fluid in the Sesia subduction channel, converting pelitic granulites back to micaschists at eclogite facies.
In summary, the textures and mineral compositions clearly reflect reactive interaction of major amounts of hydrous fluids with dry protoliths. The latter are comparable to the metapelites with Permian intrusives found in the Ivrea Zone today, supporting the long held notion of an origin at the NW-Adriatic margin.

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Structural and metamorphic subdivision of the central Sesia Zone (Aosta Valley, Italy)

Francesco Giuntoli[1], Paola Manzotti[1,2], Martin Engi[1] & Michel Ballèvre[2]

1 Institut für Geologie, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland (francesco.giuntoli@geo.unibe.ch)
2 Université de Rennes, Géosciences Rennes, UMR-CNRS 6118, University of Rennes1, Rennes Cedex, France

The Sesia Zone in the Western Alps is a continental terrane derived from the NW-Adriatic margin and polydeformed at HP conditions during Alpine convergence. Subdivisions of the Sesia Zone classically have been based on the dominant lithotypes: Eclogitic Micaschist Complex, Seconda Zona Diorito-Kinzigitica (2DK), and Gneiss Minuti Complex. However, recent work (Regis et al., 2014) on what was considered a single internal unit revealed that it comprises two or more tectonic slices that experienced substantially different PTDt-evolutions. Therefore, detailed regional petrographic and structural mapping (1:3k to 1:10k) was undertaken and combined with extensive sampling and petrochronological analysis. Results lead us to propose a detailed map for the Sesia Zone in the Aosta Valley between Val del Lys and Val d'Ayas.
A set of field criteria was developed and applied, aiming to recognize and delimit the first order tectonic units in this complex structural and metamorphic context. The approach rests on three criteria used in the field: (1) Discontinuously visible metasedimentary trails considered to be monocyclic (Permo-Mesozoic protoliths, mostly carbonates); (2) mappable high-strain zones; and (3) visible differences in metamorphic imprint. Note that a combination of these key features used, not one criterion alone, and this allows us to delimit the position of the main units in a detailed map that also includes the essence of previous maps.
We propose an Internal Complex that includes micaschists associated with mafic rocks and orthogneiss. The main foliation is always eclogitic, dipping moderately NW. It can be further subdivided into three eclogitic sheets, each 0.5–3 km thick by the presence of (most likely monometamorphic) sediments, <10–50 m thick. These are calcschist, siliceous marble and impure quartzite in the case of Col Fenêtre and siliceous dolomite marble E of Mont Prial. A local greenschist facies overprint is strong close to the tectonic contact to the

neighbouring complex, typically producing a mylonitic foliation.
The External Complex comprises mostly orthogneiss with minor paragneiss. Several discontinuous lenses of overprinted pre-Alpine amphibolite-granulite occur, representing the 2DK; these are often aligned with greenschist facies shear zones within orthogneiss. Combining these features, three main tectonic sheets are delimited in the External Complex, with the main foliation being of greenschist facies and dipping moderately SE.
An important shear zone (Barmet SZ) is identified between the above two complexes. It is made up of wedge-shaped bands of meta-granite and -diorite with few mafic boudins and lenses of paragneiss bounded by thin bands of siliceous dolomite marble. The main mylonitic foliation dips SE and is of greenschist facies, but omphacite, glaucophane, and garnet occur as relics. Towards the SW, the width of the Barmet SZ diminishes from 500 m to a few meters.
In summary, the juxtaposition between the Internal Complex and the External Complex is a major tectonic contact reflecting greenschist facies condition. The main eclogitic foliation of the Internal Complex is cut at 40-50° by the greenschist mylonitic foliation of the Barmet SZ.
Petrological work and in situ U-Th-Pb dating of accessory phases (allanite, zircon) are underway in several of these subunits of the Sesia Zone to constrain their PTDt-history.

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Salt in the passive margin, foreland basin and fold and thrust belt of the external Alps of Provence

Graham Rodney

rod.graham01@gmail.com
Rod Graham Consulting, Wallingford, United Kingdom

Triassic evaporites are a fundamental element of Alpine tectonics because they form the detachment surface for most of the Alpine thrusts, certainly the external ones. We do not see much evidence of salt at outcrop, of course, because the Alps have had too long and complicated a history for salt to remain at surface. Instead we see gypsum, 'cargneule' breccia and structural relationships that give the very strong hint that salt must once have been widespread and actively diapiric.
Diapirs are well known in the southern sub-Alpine chains (e.g. Dardeau& De Graciansky, 1990). This presentation will suggest that halokinesis is perhaps even more widespread and profound than previously thought. There is evidence of salt diapirism during both the evolution of the Jurassic rift and passive margin of the southern external Alpine zone, and also throughout the several phases of Tertiary evolution of the fold belt and foreland basin in Haute Provence.
It will be argued that the Late Jurassic sea floor looked like the Gulf of Mexico or Brazilian margins of the present day, complete with minibasins and canopies, and that much younger fragmented foreland 'piggy back' basins, including the famous Velodrome at Barles, must also have been developed as minibasins on allochthonous salt .
Most people would agree that experience of outcrop geology makes for better seismic interpretation. Where salt is concerned, the reverse is also often true. Salt is sometimes spectacularly imaged on seismic lines through the passive margins of the Gulf of Mexico and the Atlantic and we are able to see its interaction with the surrounding rocks and trace its evolution. Experience of this enables us to see outcrops – even classic Alpine outcrops - in a new light.

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Susceptibility of French Alps slopes to earthquake shaking: interactions between strong topography contrast, low tectonic loading, and low weathering context

J-R Grasso[1], C. Sue[2] L Tatard[1], C Voisin[1]

1 ISterre, Observatoire et Université Joseph Fourier, Grenoble France
2 Université de Besancon, France
jean-robert.grasso@ujf-grenoble.fr,

Landslides are a major threat to human life and infrastructure in most mountainous and hilly regions of the world. In the last century, Europe has experienced the second highest number of fatalities and the highest economic losses caused by landslides compared to other continents. As a consequence of both the increase in exposure and the possible impact of climate change, the risk associated with landslides is expected to increase.
The mechanisms that drive the landslide triggering are numerous. Their couplings result in complex patterns (e.g. the power law distribution of landslide sizes) that induced large uncertainties in the prediction of the landslide size and location and occurrence time. Within the context of a low tectonic forcing, we expect, for the French Alps, a M>6 earthquake each 300 years, and 3 M>5 events per century. Since the last glaciation epoch, (104 years ago) an isostasy uplift is the additional forcing on the mountain slopes. Because of the low weathering process, strong topography contrast as eroded by the glaciers still characterized the French Alps geomorphology.
First, when revisiting case studies of the earthquake-triggered landslides, M=4.5-6.0, 1900-2000, French Alps, we evidence:
- a smaller rate of earthquake-triggered landslide (for all the 6 sequences we studied)
- a larger triggering distance (for the triggered sequence in in the highest slope elevation slope context)than the one

expected from their magnitude as compared to worldwide database.
Second we discuss how these patterns may emerge from the interplay between the dynamics of earthquake slips and the passive slope properties over time (material and topography), including the actual climate change context.

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Evidence for Liassic to Dogger synsedimentary normal faulting in the Western Swiss Molasse Basin based on seismic interpretation

Gruber Marius, Sommaruga Anna*, Mosar Jon**

** University of Fribourg, Department of Geosciences, Earth Sciences, Chemin du Musée 6, CH-1700 Fribourg, Switzerland marius.gruber@unifr.ch*

In Liassic to Dogger times, the South-European realm is in an overall extensional stress regime associated with the opening of the central Atlantic and the Alpine Tethys basin. This leads to synsedimentary normal faulting and enhanced subsidence (e.g. Wetzel et al. 1993, eastern Jura Mountains; Mettraux & Mosar 1989, Briançonnais domain; Birkhäuser et al. 2001, Molasse basin).
This study is part of a regional scale structural analysis of the Western Molasse basin in the Canton of Fribourg. It focusses on a new structural interpretation of eleven 2D-seismic lines near the Romanens-1 well North to the frontal Subalpine Molasse thrust. The area is located in the SE part of the Swabian Basin, N of the Alemannic High.
The Romanens area is structured by different tectonic elements: [i] a NE-SW trending, SE dipping synsedimentary normal fault system confined to the Mesozoic units, [ii] a N-S trending subvertical strike-slip fault system crosscutting the Mesozoic and the Cenozoic units, [iii] a NE-SW trending, SE dipping thrust fault system in the Cenozoic units (Subalpine Molasse) and [iiii] a low-angle décollement level dipping to the SE and parallel to the dip of the Base Mesozoic horizon in Middle Triassic units (top mechanical basement s.l.).
This study places special emphasis on the NE-SW trending synsedimentary normal fault system in Mesozoic units. Former seismic interpretations already highlighted the existence of normal faults in the Romanens area (Sommaruga et al. 2012, Meier 2010) but their lateral extent remained unknown and no synsedimentary component was observed.
The normal fault system is characterized by 3 soft linked fault zones of 6-9 km length each, forming a half-graben and downthrowing the SE hangingwall by about 250m in the central part of each fault zone. Displacement dies out towards the fault tips and is relayed from one fault to the other. Thickness variations are observed on the hangingwall side in Liassic and Dogger units showing a thickening towards the fault plane while on the footwall side, these units show a thinning towards the fault plane. This configuration suggests a syndepositional NW-SE extensional event in Liassic to Dogger times which can be correlated with the rifting phase of the Tethys ocean formation (Stampfli & Hochard 2009). Upper Jurassic to Lower Cretaceous units do not show significant thickness variations.
Mesozoic and Cenozoic units are detached during the Miocene time along a décollement level located in Middle Triassic evaporites and transported towards the NW, leading to the formation of duplex- and fishtail-structures within the Muschelkalk unit and a detachement fold in the overlying units. A recent interpretation of one seismic line in the Romanens area suggests that these fishtail-structures crosscut the Mesozoic and Cenozoic units (Mosar et al. 2014). Further investigation will focus on the influence of inherited normal faults (in the Mesozoic layers and at the Base Mesozoic horizon) on the development of inversion structures (fishtails in this case) and on the lateral extent of these structures. Studies further to the NE at the edge of the Permo-Carboniferous trough of N Switzerland have revealed the importance of this genetic link.

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Architecture and reactivation of an upper plate distal rifted margin: the example of the French-Italian Briançonnais and Prepiemontais domains in the W-Alps

Haupert I., Manatschal G., Decarlis A., Epin M.E.,

IPGS/EOST, Université de Strasbourg, rue Blessig 1, F-67084 Strasbourg Cedex, France - haupert@unistra.fr

Although it is generally accepted that most distal, magma-poor rifted margins are asymmetric and can be divided into lower and upper plate margins, little is known about the details of how and when this asymmetry evolves, how upper and lower plate margins can be distinguished and what are the characteristic architectural features of these margins. This is due to the fact that most studies focused on so called lower plate margins, while the upper plate margins remained less well understood, mainly due to the

lack of access to open domain high quality seismic data and drill hole data. In our study we show that the Briançonnais and Prepiemontais units in the Western Alps preserve remnants of a Jurassic upper plate margin belonging to the distal European margin.
In the presentation we define the characteristics of upper plate, magma-poor rifted margins using seismic examples and km-scale outcrops in the Alps and show examples exposed in the Briançonnais and Prepiemontais units in the Briançonnais area in SW France. The commonalities between the seismic geometries and the field observations enable to propose new interpretations for the nature of the unconformities previously described from the Briançonnas and Prepiemontais units as well as to propose a re-interpretation of the Alpine evolution that includes the importance of rift-inheritance during the reactivation of the European margin and the stacking of the different rift domains of the former European margin.

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Coupling between tectonics and erosion in the Alps and the eastern Himalayan syntax.

Frederic Herman and Georgina King

Université of Lausanne

The idea that mountain topography is the result of positive feedbacks between climate, erosion and tectonics comes not only from theoretical models, but also from the observation that rugged topography often spatially coincides with high precipitation, high rock uplift and high erosion rates. Unfortunately, such an observation only constitutes circumstantial evidence, rather than demonstrating feedbacks. Here we will discuss whether erosion can have an impact on tectonics for two sites where we have quantified how erosion rates vary in space and time. First, we will show that high erosion rates (i.e. > 1 mm/yr) in the western Alps during the Quaternary may be the result of the combined effects of slab break-off and the intensification of Quaternary glaciations. Increased rock uplift rates due to slab break-off and enhanced cooling enabled to maintain a large ice accumulation area that sustained a high ice flux, and thus glacial erosion rates, during the last 1 to 2 Myr. Second, we will show how erosion varied in space in the eastern Himalayan syntax, using the newly developed OSL-multi-thermochronometry technique. There, it has been proposed that feedbacks between tectonic, rheological, thermal, and surface processes have developed where sufficiently rapid tectonic uplift and focused erosion have been superimposed and spatially stationary; which is known as the 'tectonic aneurysm' model. Our new results show that, instead, the locus of high erosion rates has been migrating northward in the last 500 kyr. This results implies, that although the combined effects high rock uplift rates and river incision due to high water discharge and steep slopes can lead to high erosion rates, geomorphic processes are not necessarily able to feedback onto tectonics, as implied by numerical and analogue models.

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Crust fragmentation and block rotation pattern along intra-arc strike-slip faults arising from oblique subduction: Paleomagnetic evidence from the Liquiñe-Ofqui fault zone (Southern Chile, 38°-41°S)

Hernandez-Moreno, Catalina[1], Speranza, Fabio[1], Di Chiara, Anita[1,2]

1- Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy
Email: catalina.hernandezmoreno@ingv.it
2- Now at Department of Geophysics of São Paulo, São Paulo (Brazil)

A fundamental component of tectonic deformation occurs in strike-slip tectonic domains, occurring in about 50% of all modern subduction zones, even in cases where obliquity is less than 45° [Jarrard, 1986]. According to literature data, intra-arc strike-slip fault activity yields frequently, but not always, vertical-axis rotation of crustal blocks. Although several kinematic models have attempted to predict the distribution, sense, and amount of rotation inside the deforming zone of strike-slip faults [Nelson and Jones, 1987; Hernandez-Moreno et al., 2014], their kinematics and rotation pattern remain nowadays highly controversial.
Here we report on a paleomagnetic investigation of the dextral Liquiñe-Ofqui fault zone (LOFZ) in Southern Chile, interpreted to be the result of strain partitioning of oblique oceanic subduction (Figure 1). This is one of the most active convergent plate boundaries of Earth, where the oceanic Nazca Plate is subducting obliquely beneath the continental South American Plate since at least 50 Ma. We paleomagnetically sampled 55 sites (553 samples) among Oligocene to Pleistocene volcanics and Miocene granites at a maximum distance of 20 km from the LOFZ, and at both sides of it between 38°S and 41°S. Rotations with respect to South America, evaluated for 36 successful sites, show that crust around the LOFZ is fragmented in small blocks, ~1 to 10 km in size. While some blocks (at both fault edges) undergo very large 150°-170° rotations, others do not rotate, even adjacent to fault walls.
We infer that rotations affected equidimensional blocks, while elongated crust slivers were translated subparallel to the LOFZ, without rotating. Rotation pattern across the LOFZ is markedly asymmetric. It cannot be accounted by any of the kinematic models of block rotation proposed so far for dextral strike-slip faults. East of the fault and adjacent to it, rotations are up to 150°-170° clockwise (CW), and fade out ~10 km east of fault. Conversely, crust west of the LOFZ is cut by seismically active NW-SE sinistral antithetic faults, and yields counterclockwise (CCW) rotations up to 170° at 8–10 km from LOFZ, besides the unrotated blocks.

These data support a quasi-continuous crust kinematics east of the LOFZ, controlled by the fault itself. Conversely, data west of the fault show that the LOFZ actually does not drive the CCW rotations that are likely the consequence of the kinematics of (or within) the Chiloé Block.

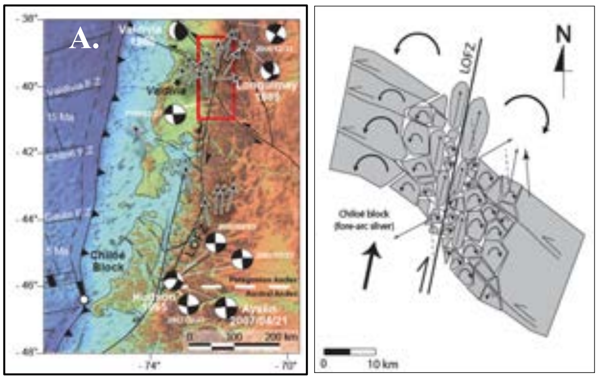

Figure 1. A) Southern Chile tectonic setting. Red box indicates the study area. White stroke arrows represent paleomagnetic rotations. B) Quasi-continuous block rotation model of the crust around the LOFZ based on paleomagnetically observed rotations. LOFZ Liquiñe-Ofqui fault zone.

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Depositional environments created by the disruption of the Steinalm carbonate platform in the Middle Triassic (Aggtelek–Rudabánya Hills, NE Hungary) – Lithofacies and microfacies associations

Balázs, Horváth[1], Kinga, Hips[2], László, Fodor[2]

1 Eötvös Loránd University, H-1117 Budapest, Pázmány Péter sétány 1/c; kyklad@gmail.com
2 Geological Geophysical and Space Science Research Group of The Hungarian Academy of Sciences, H-1117 Budapest

In the Middle Anisian (Pelsonian) the onset of the Neotethyan rifting caused the drowning and dissection of the Steinalm carbonate ramp along the northern shelf of the Neotethys Ocean. As a result of the extensional tectonic processes the basement became differentiated and sedimentation occurred on half-graben morphology.
Recent mapping, drilling core and thin section analysis of the drowning-related succession revealed several specific types of lithofacies and microfacies in the Aggtelek–Rudabánya Hills, NE Hungary. These depositions can be divided into four lithofacies associations. L1: red, purplish red, greenish grey and black argillaceous limestone; L2: light grey lithoclasts of Steinalm limestone in red, purplish red argillaceous limestone; L3 pink, beige crinoid-brachiopod limestone and L4: beige, light grey coquina beds. The microfacies types of lithofacies L1 and L2 are mudstone, bioclastic wackestone and radiolarian packstone which represent pelagic, deep-water sedimentation. Lithofacies L1 developed inside the newly formed basins whereas L2 is related to the toe of structural highs with escarpments. Lithofacies L3 is built by crinoid-brachiopod wackestone which indicates deposition on slopes of structural highs occupied by brachiopod and crinoid gardens. Lithofacies L4 comprises bivalve packstone-grainstone and brachiopod-crinoid-bivalve grainstone which were likely deposited via short-term depositional events, e.g. storms, turbidites and mass flows. During the Illyrian these lithofacies types were gradually replaced by clotted micrite boundstone (Horváth and Hips, 2015) which marks the build-up of the microbial boundstone dominated carbonate slope systems.

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Mechanics of Alpine uplift

Husson, Laurent[1]; Sternai, Pietro[2,3]; Becker, Thorsten[4]; Faccenna, Claudio[5], Guillot, Stpéhane[1]

(1) ISTerre, CNRS, Grenoble, France, laurent.husson@ujf-grenoble.fr
(2) CALTECH
(3) University of Cambridge
(4) University of Southern California, Los Angeles, USA
(5) Universita Roma 3

The Alps are uplifting at a fast rate, although crustal tectonics is moderate, if any. Because this observation rules out the most serious contributor to vertical ground motion, many authors recently invoked alternative mechanisms, "deep processes" in particular. Here we review the observations and possible mechanisms, with a particular emphasis on dynamic topography. It is unlikely that a single process may explain the current vertical kinematics in the Alps.

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Evidence for Eoalpine top to the WNW thrusting and top to the ESE normal faulting in the Gurktal nappes (Drauzug-Gurktal nappe system, Upper Austro-Alpine, Austria)

Iglseder, C.[1] & Huet, B.[2]

1: Dep. of HardRock Geology, Geol. Survey Austria, Neulinggasse 38, A-1030 Vienna Austria christoph.iglseder@geologie.ac.at;
2: Department of Geodynamics and Sedimentology, University of Vienna, Althanstraße 14, A-1090 Vienna, Austria,

The Eoalpine kinematics in the Austro-Alpine is still purely constrained and still a matter of debate. In this communication we present new structural data from the Gurktal nappes, indicating top to the WNW thrusting followed by top to the ESE normal faulting in the uppermost part of the Eoalpine orogenic wedge.
The Gurktal nappes extend over the geographic region of the Gurktal Alps, located in the southern part of Austria (Styria, Carinthia). The Gurktal nappes are part of the Drauzug-Gurktal nappe system and represent the uppermost tectonic unit of the Upper Austro-Alpine nappes. They are underlain by nappes of the Ötztal-Bundschuh nappe system to the W and by the Koralpe-Wölz nappe system to the N, E and SW. The investigated area is located in the region between Turrach and Ebene Reichenau (UTM-map sheet Radenthein NL-33-04-06). Lithostratigraphically from the footwall to the hanging wall Devonian impure marbles and phyllonitic micaschists of the Murau nappe are overlain by metaconglomerates, metasandstones and anthracite bearing phyllites of the upper Carboniferous Stangnock formation (STF) belonging to the Königstuhl subnappe. The top unit (Stolzalpe nappe) is represented by interbedded metasandstones, metasiltstones, phyllites and graphitic schists of the Spielriegel complex, metavolcanic rocks of the Kaser-Eisenhut complex covered by postvariscan sediments (STF).
At Mitterturrach along the state road B95 (UTM N5199548; E415228) a shear zone between the Königstuhl subnappe and the overlying Stolzalpe nappe is exposed. Ductile as well as brittle features document a long lasting story which is also constrained by deformation within the Stolzalpe nappe. Early structures related to Variscan times are documented in the hanging wall with fold axes striking (W)NW-(E)SE and axial planes that are superimposed by later folding. The later asymmetric folds with NNE-SSW fold axis and axial planes dipping to (E)SE indicate NNE-SSW shortening. It is correlated with brittle-ductile top to the WNW thrusting in the nappe contact indicated by SC-fabrics, C´-type shear planes (with striation and fibrous quartz) and clast-geometries. This event is post Carboniferous and therefore attributed to Eoalpine deformation. The thrust is likely to have localised in carbon-rich lithologies (graphitic schists, anthracitic phyllites) observed in both units. Reactivation of former structures as normal faults, neoformation of normal faults and C´-type shear planes crosscutting the older structures, indicate a change in tectonic regime with WNW-ESE extension, dominated by top to the ESE shearing. This extensional tectonic event is also found in impure calcite marbles mylonites of the Murau nappe.
We integrate these new data together with previously published data (Ratschbacher & Neubauer, 1989), maximum temperature data (Rantitsch & Russegger, 2000) and Ar-Ar cooling ages for developing a model evolution of the upper part of the Eoalpine orogene during upper Cretaceous.

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Evidence of hydrothermal fluid flow in distal rifted margins: the case study of Err nappe.

*Incerpi Nicolò[1,2,] *, Martire Luca[1], Manatschal Gianreto[2], Bernasconi Stefano[3]*

1 Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, 10125 Torino - Italy
*2 EOST-IPGS, Université de Strasbourg, 1 Rue du Blessig, 67084 Strasbourg Cedex – France. *nincerpi@unistra.fr*
3 Geological Inst, ETH Zurich, Sonneggst. 5, 8092 Zurich – Switzerland

In the last decades the increasing availability of high resolution seismic data and deep drill hole data have allowed to understand with greater detail the architecture of present-day passive rifted margins and to propose new models about their tectono-stratigraphic evolution. These models show how a multiphase evolution of rift systems led to a complex architecture: a proximal 30 km-thick crust separated, by a necking zone, from a thinned continental crust (<10km), followed by a wide transition zone between the continental and oceanic crusts where mantle exhumation occurs. The thermal evolution of distal margins is, however, very poorly constrained, although the presence of hydrothermal systems seems to play a key role in determining the heat fluxes. A deeper and more detailed study of such systems is thus fundamental to reconstruct the thermal and diagenetic evolution of the sedimentary successions lying above these margins. Therefore, the main aim of this study is the characterization of the hydrothermal systems in the Adriatic paleomargin and their evolution relatively to continental extension in order to figure out the relations among the hydrothermal products due to fluid flow, the stratigraphy and the main tectonic structures. The studied area is located in the southeastern part of Switzerland, where basement rocks and overlying sedimentary successions are spectacularly exposed. Since this domain escaped strong Alpine metamorphic overprint, sedimentary and structural features related to the Jurassic evolution of the margin are very well preserved. A detailed sampling was carried out on carbonate rocks cropping out along the entire margin, from the most distal to the proximal part, in order to get a complete dataset in different tectono-stratigraphic settings. Two sites in the Err nappe have been studied more in detail: Piz Val Lunga and Fuorcla Cotschna. We are focusing, in particular, on the interaction between fluids and pre- and syn-rift sediments that are, respectively, Triassic dolostones preserved as extensional allochthons, and basin-filling sedimentary breccias that reworked both the footwall and hanging wall of the detachment fault. Understanding the degree of rock-fluid interplay is crucial to develop models about the thermal history of the area. Within this context, the main goal is then to discern among different types of hydrothermal products such as cements, veins and replacement minerals that could testify any rock-fluid interaction. Field evidence, petrography and cathodoluminescence investigations reveal a strong heterogeneity in the composition of the fluids that passed along the detachment and through the sediments. Samples from the Err nappe contain saddle dolomite, sparry calcite, quartz, chalcedony and albite, suggesting a complex frame in which dolomitization, calcitization and silicification characterized the long evolution of the margin. Crosscutting relationships provide evidence of how these products refer to different steps of the evolution of the margin, from very early stages during the onset of extension until the Alpine orogeny. O and C isotopic analysis were performed on pre-rift Triassic carbonate and pre- to syn-rift calcite and dolomite veins and cements. The resulting slightly positive C and strong negative O values point to a hydrothermal origin of the fluids flowing through the sediments. These data can be easily compared with those coming from present-day Iberia continental margin (ODP Leg 103). Furthermore, we will illustrate new geochemical (main and trace elements, REE), isotopic (Sr) and fluid inclusions data that allow to better constrain the hydrothermal fluid flow pattern in the complex evolution of the Adriatic margin.

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Diamond from Pohorje confirms UHPM and deep subduction of continental crust in the Eastern Alps

Janàk, Marian[1], Froitzheim, Nikolaus[2], Yoshida, Kenta[3], Sasinkovà, Vlasta[4], Nosko, Martin[5], Kobayashi, Tomoyuki[6], Hiralima, Takao[3], Vrabec, Mirijam[7]

1 Geological Institute, Slovak Academy of Sciences, Dúbravská 9, Bratislava 45, Slovak Republic, marian.janak@savba.sk
2 Steinmann-Institut, Universität Bonn, , D-53115 Bonn, Germany
3 Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
4 Institute of Chemistry, Slovak Academy of Sciences, Dúbravská 9, 840 05 Bratislava, Slovak Republic
5 Institute of Materials and Machine Mechanics, Slovak Academy of Sciences, Dúbravská 9, 840 05 Bratislava, Slovak Republic
6 Faculty of Health & Sports, Nagoya Gakuin University, Aichi 480-1298 Japan
7 Department of Geology, University of Ljubljana, Askerceva 12, SI-1000 Ljubljana, Slovenia

Diamond and moissanite were found in metapelitic crustal rocks of Pohorje Mountains in the Eastern Alps (Janák et al., 2015) hosting ultrahigh-pressure (UHP) eclogite and garnet peridotite. Diamond occurs as inclusions in garnet, being heterogeneously distributed and showing pinkish, yellowish to brownish colour. From the microscopic, SEM and Raman spectroscopic observations it is clear that diamond inclusions occur in-situ either as single-crystal inclusions or as composed polyphase inclusions of diamond + moissanite (SiC) and diamond + carbon dioxide (CO2) + methane (CH4). Diamonds are characterised by sharp Raman peaks mostly centered between 1332 and 1330 cm-1, some of them are partly graphitised. Co-existence of diamond and moissanite as fluid-inclusion daughter minerals implies their crystallization from a supercritical COH-fluid at reducing conditions (Janák et al., 2015).

Calculated P-T conditions for diamond-bearing gneisses based on thermodynamic modelling show pressures of ≥3.5 GPa at 800–850 °C, and are in agreement with P-T data for eclogites (3.7 GPa at 800–850 °C; Vrabec et al., 2012) and garnet peridotites (4.0 GPa at 900 °C; Janák et al., 2006). The diamonds formed in carbonaceous sediments at UHP metamorphic conditions, as a consequence of intracontinental, SE- dipping subduction of Austroalpine units in the Late Cretaceous (c. 95–92 Ma). The finding of diamonds confirms UHPM in Pohorje (Janák et al., 2004), the most deeply subducted part of the Austroalpine units of the Alps.

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Formation of necking zones during lithospheric rifting

Jaquet, Yoann; Duretz, Thibault; Schmalholz, Stefan

Institute of Earth Sciences, University of Lausanne, CH-1015 Lausanne, yoann.jaquet@unil.ch

Although numerous models of rift formation have been proposed, the formation of necking zones during rifting has not been quantified in detail until now. However, necking zones are a characteristic feature and commonly observed in both fossil and present-day passive margins. It is thus of primary interest to understand and quantify the mechanisms that control the formation of necking zones. In this study, we use one-dimensional (1-D) analytical solutions for necking, 2-D numerical simulations of rifting considering only power-law viscous flow laws and 2-D rifting models considering viscoelastoplastic rheologies and thermo-mechanical coupling. These models of different thermo-mechanical complexity are applied to investigate the evolution of necking zones and to quantify their geometrical evolution during lithospheric extension. The thinning rate of the crust during lithospheric rifting and the final width of the necking zones are calculated and compared for the 1-D and 2-D models. Our results of a systematic numerical analysis indicate that the width of the necking zone is relatively independent on the model parameters and is around 50 km for typical lithospheric rifting conditions (e.g. extension rate, initial temperature etc.). The calculated necking width in the order of several tens to hundred kilometers agrees with field observations and reconstructions of the necking zones in the passive margins of the Alpine Tethys. The application of the presented analytical and numerical solutions for necking to the passive margin evolution of the Alpine Tethys is discussed.

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Strain partitioning in the crust during continental collision: Insight from 2D numerical modeling

Jie, Liao & Taras, Gerya

Sonneggstr. 5, 8092, Zurich, Switzerland, Institute of Geophysics, ETH Zurich, jie.liao@erdw.ethz.ch

In the central Alps, crustal shortening during the post-collision process varies along strike (Rosenberg and Kissling, 2013). Shortening pattern is gradually changed from upper plate crustal shortening (UPCS) in the east (e.g. Engadine profile in Rosenberg and Kissling, 2013) to lower plate crustal shortening (LPCS) in the west (e.g. Simplon profile Rosenberg and Kissling, 2013). The addressed question here is to a first order what controls UPCS or LPCS? Does it more depend on geological structure or physical parameters? We use a 2D thermo-mechanical coupled numerical model (Gerya and Yuen, 2007) to investigate the crustal strain partitioning during collision. Several important model parameters are tested, such as the lithospheric rheological structure, the lithospheric thermal structure, the convergence rate and the weak zone (decoupling two continental plates) geometry. Particular attention is paid on the influence of crustal strength (i.e. strength contrast between two continental plates) on shortening partitioning.

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Crustal structure of the Alps from Ambient Noise Tomography

Kaestle, Emanuel; Boschi, Lapo; Bellahsen, Nicolas; Rosenberg, Claudio

4 Place Jussieu, 75252 Paris Cedex 05, iSTeP, UPMC, Paris.

The ambient noise method has become very popular in the last two decades. With a growing number of seismic stations and easy availability of long records, it has become applicable in many regions of the world. Especially projects like the USArray create ideal conditions for Ambient Noise tomography. The signal for this method is created by microseisms, which originate from the permanent interaction of atmosphere, ocean swell and solid ground. In comparison with classical earthquake tomography, Ambient Noise is most energetic in the short period band. This means, it allows to image very shallow structures, from the surface to the upper mantle. In combination with the high lateral resolution of surface wave tomography, we are able to resolve the crustal structure underneath the Alps. We show extensions and depth of sedimentary basins at the border of the Alpine orogen, as well as variations in the crustal thickness. In this context we aim to resolve wave speed differences between the Adriatic and European Plate in the Eastern Alps and trace their signature at depth.
By using all the available stations and inverting both for Love- and Rayleigh waves, we stabilize our results further. The processing is largely automated and will highly profit from all future efforts like the AlpArray project. This study is an extension of earlier efforts by Molinari (2011), Verbeke (2012), Boschi (2009) and co-workers, and represents the next step to close the gap between very localized seismic studies and largescale earthquake tomography.

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The Pleistocene Mitterberg deposits: Tectonic control, provenance analysis and depositional processes (Upper Enns Valley, Austria)

Keil, M., Neubauer, F.

University of Salzburg, Dept. Geography and Geology, 5020 Salzburg, Austria; melanie.keil2@sbg.ac.at; franz.neubauer@sbg.ac.at

The ENE-trending Salzach-Enns-Mariazell-Puchberg (SEMP) fault is an orogen-parallel (sinistral, then dextral) strike-slip fault facilitating eastward lateral extrusion. Up to now, no releasing nor restraining bends were reported although the fault obviously curved. Here, we present the Mitterberg, which likely formed on a right-stepping releasing bend on the late-stage (Pleistocene) dextral activation of the SEMP fault. Quaternary glaciations combined with neotectonic activity formed the landscape of the Upper Enns Valley (Eastern Alps). The SEMP fault separates the Niedere Tauern block with amphibolite- and greenschist facies grade metamorphic rocks from the Northern Calcareous Alps. The Mitterberg lies between the paleosurfaces south and north of the Upper Enns Valley. It counts as a relic of a continuous Pleistocene valley bottom, now 850 meters above the present-day Enns Valley. As the Ramsau plateau farther west is supposed to have formed a continuous valley bottom with the southern paleosurfaces as well, a comparison of the conglomerates suggests varying sources of sediment deposition. Provenance analysis of the Ramsau Conglomerate results in a predominant percentage of crystalline clasts, indicating primarily the provenance from the medium and low-grade metamorphic gneissic terrain of the Niedere Tauern to the south (61% crystalline rocks, 24% unmetamorphic carbonates, 15 % Permian to Lower Triassic sandstones). Provenance analysis from Mitterberg shows a slight variation (60% crystalline rocks, 26% unmetamorphic carbonates, 13% sandstones); however, there is a significant difference in clast composition. High-grade metamorphic diorite-gneiss is not present in the Ramsau Conglomerate; frequently appearing orthogneiss on Mitterberg is present scarcely in the former. Significant for the conglomerate on Mitterberg is the occurrence of carbonates derived from the Northern Calcareous Alps like Gutenstein and Hallstatt Limestone Fms. as well as Fellerbach Formation from the base of the Northern Calcareous Alps. The dearth of fine fractions identifies the Mitterberg as an older deposit and not as a "Niederterrasse" as suggested by other authors before. We conclude that the sedimentary pattern has undergone a change between Pleistocene and Holocene, and that the northern side of the Mitterberg represents a wind gap. The Holocene Enns River dissected the Pleistocene valley infill later. At Mitterberg, cross bedding indicates clearly bipolar transport directions, whereas in the Ramsau Conglomerate the directions of sediment flow vary widely. The conglomerate on Mitterberg also records tectonic deformation indicated by normal faults and photolineaments. A prominent NW-trending fault cuts the Mitterberg block in the west, geomorphic evidence argues for a dextral displacement. An interesting result is that there is no evidence for sinistral strike-slip along steeply NNW-dipping normal faults as could be expected from the mostly sinistral nature of the SEMP fault.

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From Jurassic accretion to Cretaceous back-thrust: tectonic consequences of 220 Ma rhyolite clasts from Neotethyan melanges

Kövér Szilvia[1], László Fodor[1], Norbert Zajzon[2]

1-1117 Budapest, Pázmány P. 1/c, MTA-ELTE Geological, Geophysical and Space Science Research Group, koversz@yahoo.com
2- 515 Institute of Mineralogy and Geology, Univ of Miskolc Hungary

Middle to early Late Jurassic coarse-grained (meta-) sedimentary units were investigated in NE Hungary and SE Slovakia. They show similar lithological character, but according to present knowledge, they thrust onto different margins of the Neotethys Ocean during Late Jurassic – Early Cretaceous. At present, these siliciclastic rocks form different nappe units. The Mónosbél nappe is sandwiched between a Dinaridic Palaeozoic – Mesozoic succession (Bükk) and the Western Vardar ophiolite nappe. On the other hand, the Meliata nappe is part of the Western Carpathian nappe stack, which presumably formed the northern margin of the Neotethyan Ocean.
Geochemical analysis and U-Pb age dating of rhyolite clasts deriving from different nappe units indicate potential common source area: the Dinaridic – South Alpine margin. The supposed source area gives a possibility to question certain plate tectonic reconstructions and suggest new speculations. While the ofiolite obduction onto the southern (Dinaridic) margin is proved to be Late Jurassic, only Cretaceous nappe contacts have been documented on the northern (Western Carpathian) margin, although subduction also started in the Middle Jurassic. It can be interpreted in two ways:
a) All the siliciclastic, sedimentary mélange units (both Meliata and Mónosbél) first accreted onto the Dinaridic margin during the Late Jurassic, then later, thrust on top of the northern margin during the Cretaceous deformation.
b) Alternatively, the Western Carpathian Meliata unit did not take part in the first, Dinaridic thrust phase, but was cut from its original sedimentation area by a strike-slip fault. Such a fault has been postulated in the Eastern Alps by seveal authors (Stüwe & Schuster 2010) to explain subduction process of the Austroalpine units. This postulated strike-slip fault would have late Jurassic age, which would post-date sedimentation and pre-date early Cretaceous metamorphism. In this scenario, Meliata unit might have experienced one major thrusting deformation onto Carpathian units, possibly during the early(?) Cretaceous.

The research project is supported by Hungarian National Fund OTKA 113013.

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The deep structure of the Pamir and Hindu Kush mountains, central Asia – about the fate of continental lithosphere during collision

Kufner, Sofia-Katerina[1]; Schurr, Bernd[1]; Sippl, Christian[1] †; Yuan, Xiaohui[1]; Ratschbacher, Lothar[2]; Mohammad Akbar, Arib[3]; Ischuk, Anatoly[4]; Murodkulov, Shokhrukh[4]; Schneider, Felix[1] ‡; Mechie, James[1]; Tilmann, Frederik[1,5]; Bezada, Max[6]

(1) Deutsches GFZ Potsdam, 14473, Germany. kufner@gfz-potsdam.de
(2) Geologie, TU Bergakademie Freiberg, Germany
(3) Tajik Technical Univ, Academics Rajabovs Republic of Tajikistan
(4) Tajik Academy of Sciences, Republic of Tajikistan
(5) Freie Universität Berlin, Germany
(6) University of Minnesota, Minneapolis, MN 55455, USA
† Now at Australian National Univ, ‡ Now at Univ Wien, Austria

The Pamir-Hindu Kush mountains, located north of the western Himalayan syntaxis, are one of the most puzzling regions in the Indian-Eurasian collision zone. In contrast to Himalaya and Tibet further to the east, Pamir and Hindu Kush feature intense intermediate depth seismicity, reaching ~270 km depth [1,2]. While the Pamir seismicity seems to be hosted in lower crustal material, dipping from the Eurasian side [3], the affinity of the Hindu Kush seismic zone is debated. Further, as intermediate depth seismicity is generally confined to oceanic subduction zones, the mechanism driving the Pamir-Hindu Kush seismicity, as well as the tectonic relation between the two orogenes is still enigmatic. Here we use data recorded by three temporary seismic networks (2008-2010 and 2012-2014) and several permanent stations to illuminate the deep structure in the region using a variety of geophysical methods. Our joint network amounts to 180 sites and covers not only the Pamir and surrounding region but also includes stations in Afghanistan, on top of the seismically active region, allowing precise earthquake localization. About 4000 earthquake hypocenters enable for the first time to distinguish clearly between two separated, seismically active structures beneath Pamir and Hindu Kush, dipping from the Asian and Indian side, respectively. This constellation might indicate ongoing continental subduction with opposite polarity in direct vicinity. High resolution teleseismic tomography images a strong high velocity anomaly (HVA) beneath the deepest Hindu Kush earthquakes, reaching to the transition zone but thinning out at ~250 km depth where seismicity is most intense. A stress inversion of ~300 earthquake focal mechanisms revealed a purely down-dip extensional stress regime in the Hindu Kush, indicating that the deep HVA can still exert stress on the shallow, seismically active structure. We suggest that these observations show an ongoing slab detachment. By contrast, beneath the Pamir a broad, arcuate high velocity slab is imaged. It is northward offset from the Hindu Kush anomaly, reaches only depths of ~400 km and is torn apart in its center. Where this vertical tear develops, stress is along arc extensional. This situation clearly contrasts to the inferred slab detachment in the Hindu Kush. Hence our observations suggest that two contrasting modes of lithospheric convergence might currently be active in direct vicinity beneath the Pamir and Hindu Kush mountains.

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Permian metamorphism in fragments of continental crust in the Western Alps

Kunz B.E., Manzotti P., von Niederhäusern B., Burn M., Giuntoli F. and Engi M.

Institute of Geological Sciences, Univ. of Bern (engi@geo.unibe.ch)

During the late Paleozoic the Adriatic continental margin underwent lithospheric thinning accompanied by asthenospheric upwelling, causing a high thermal regime in the continental crust. This produced high-temperature, medium-pressure (HTMP) metamorphism and partial melting in the lower crust as well as extensive magmatic activity affecting all crustal levels.

Evidence of a late Carboniferous to early Permian regional metamorphic imprint has been extensively recorded and well established in the Southern Alps and Austroalpine domain of the Eastern Alps. In the Western Alps, Permian metamorphism has been repeatedly inferred for Adria-derived units, but the age of this metamorphism has been only very locally well established (Zucali et al., 2011; Manzotti et al., 2012). The present study aims to add reliable age data for this regional metamorphism. The main focus lies on the IIDK and Valpelline Series (Sesia-Dent Blanche nappes), as they correspond to lower continental crust, where the Permian metamorphic imprint was strongest and the Alpine imprint is rather weak. However, a number of samples from eclogitic micaschists of the Sesia Zone and the Emilius klippe are also included in this study. Here, an extensive dataset of U-Pb ages for metamorphic zircon is presented. To estimate P–T conditions of this metamorphism, the age data are complemented by Ti-in-Zrn-thermometry, Zr-in-Rt-thermometry and with P–T-estimates based on mineral assemblages. Clastic meta-sediments (mostly metapelites) were sampled to ensure sufficient amounts of zircon and to simplify comparisons within the dataset. The studied zircons show growth zones with textural features typical of metamorphic growth such as dark CL-emission and sector or fir-tree zoning. Some zircons also preserve detrital cores with a wide range of ages and textures. Growth zones related to Permian metamorphism range in age between 310–250 Ma. However, within this time interval, individual samples often show zircon growth in two or three age generations. Ages older than 300 Ma, reflecting an early/first phase of zircon growth, are sparse. The main crystallisation phase of zircon, present in all samples, was between 290–270 Ma, whereas younger ages (<270 Ma) again are not found in all samples. Ti-in-Zrn-thermometry yields temperatures of 650–800°C, whereas Zr-in-Rt temperatures are slightly higher, 650–850°C. Taken together with preserved mineral assemblages (grt + prismatic sil + bt + pl + qtz + kfs + rt + zrn + Fe-Ti oxides), these temperature estimates suggest uppermost amphibolite to granulite facies conditions for the Permian metamorphism. Kyanite is absent in mineral assemblages, and cordierite formed on retrogression only; these observations indicate a pressure range between 5–11 kbar. The zircon record in metapelites from units that experienced an Alpine eclogite facies imprint is more difficult to read, due to resorption and additional HP-overgrowth rims. However, pre-Alpine zircon relics preserve growth zones with ages and textures similar to those from the IIDK, Valpelline and Ivrea Zone. The data presented show that Permian HTMP metamorphism is abundant and widely distributed in the Western Alps, in units derived from the Adriatic margin.

The age and P–T estimates show many similarities with data reported for the Southern Alps, notably the Kinzigite Formation in the Ivrea Zone.

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Petrochronological investigations of the geodynamic processes leading to the exhumation of the Liguro-Piedmontais oceanic prism during Alpine collision

Lanari Pierre[1], Verly Aude[2], Riel Nicolas[3], Dumont Thierry[2], Rolland Yann[4], Schwartz Stephane[2], Engi Martin[1]

1 Dept. of Geological Sciences, University of Bern, Baltzerstrasse 1-3, CH-3012 Bern;
2 ISTerre, University of Grenoble 1, CNRS, 1381 rue de la Piscine, 38041 Grenoble, France.
3 Dept. of Earth Sciences, Durham University, Durham DH1 3LE, United Kingdom.
4 Géoazur, UMR7329-CNRS, UNS, 250 rue Albert Einstein, Sophia Antipolis, 06560 Valbonne France.

The study of the tectono-metamorphic history of the Alpine metamorphic belt, involving oceanic subduction and continental collision processes, requires knowledge of detailed Pressure-Temperature-time-deformation (P-T-t-ε) paths recorded by different units across the internal zones. The characterization of detailed P-T-t-ε paths aims to determine the time scales and rates of metamorphism and to provide food for thought to build conceptual geodynamic models. However, this task is particularly challenging in low-grade rocks for both thermobarometry and geochronology. For instance, metapelites at greenschist facies metamorphic conditions show a narrow spectrum of Alpine metamorphic minerals, notably quartz, chlorite and K-white mica, in addition to some relics. To obtain reliable P-T estimates, a combination of methods is required, usefully combining Raman study of Carbonaceous Material, chemical analysis in standardized X-ray maps, and multi-equilibrium thermodynamic modelling (by inverse and forward techniques) of chlorite and K-white mica. In order to date specific P-T stages, it is critical to use in situ dating techniques. High-resolution geochronology was applied including U-Th-Pb age-dating of allanite by LA-ICP-MS analysis in combination with single-grain 40Ar/39Ar dating (step heating).

In the French western Alps, the Briançonnais zone is a remnant of the collision wedge, while the Liguro-Piedmontais zone is a fossil oceanic subduction wedge. Metapelites from these two complexes were investigated to constrain the individual P-T-t-ε paths recorded in each tectonic slice. This study focussed on deciphering four tectono-metamorphic units in the Briançonnais zone and five within the Schistes lustrés complex (blueschist facies). The external part of the Briançonais zone records Alpine pressure peak conditions at 275°C and 0.6 GPa. These conditions, intermediate between a subduction and collision geothermal gradient, suggest incorporation late in the Alpine collision, in line with the paleogeographic position. In the most internal units the pressure peak is reached earlier, at ca. 45 Ma. This HP peak has been recorded in both continental units (PdP Ambin, Vanoise and Acceglio slices) and in the oceanic prism (Agnel slice) suggesting the occurrence of a major geodynamic transition at 45 Ma marked by the initiation of large-scale exhumation. In the oceanic units, prograde P-T-t conditions of the oceanic subduction were obtained from phengite + albite + quartz assemblages, which are locally preserved in isoclinal F1 folds. This burial stage occurs earlier, at the onset of continental subduction (~68 Ma), marking another major geodynamic change within the subduction zone. Little evidence of this early stage is preserved because of the strong fluid-rock interaction occurring during the late exhumation of the prism. P-T-t conditions of this event were characterized in the Acceglio zone and in the overlying Schistes Lustrés (Verly et al., 2015). This stage occurs at ca. 34 Ma under mid-crustal conditions (400°C and 0.7 GPa), a few million years before the Penninic front was activated.

These new constraints nourish a geodynamic model of the burial and exhumation of these units, based on metamorphic rates calculated from the P-T-t data. The interesting implications of the new model are that (1) the burial history of the oceanic wedge is not continuous and seems to be intimately linked with the initiation of continental subduction; (2) the exhumation history of the continental and ocean-derived units is clearly linked: both start in the most internal parts at ca. 45 Ma.

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Mapping the syntectonic successions atop the Eclogite Belt: the Tertiary Piedmont Basin of the Ligurian Alps (Italy)

Marco G. Malusà [a], Laura Federico [b], Laura Crispini [b], Michele Piazza [b], Nicolò Frattolillo [a], Michele Milani [a], Matteo Zampicinini ,[a] Giovanni Capponi [b]

a Dept of Earth and Environmental Sciences, Univ of Milano-Bicocca, Milan, Italy (marco.malusa@unimib.it)
b DISTAV Univ. of Genova, Corso Europa 26, 16132 Genova, Italy.

Syntectonic sedimentary successions provide first-order constraints to investigate the mechanisms of (U)HP rock exhumation, and unambiguous documentation of orogen erosion and topographic growth through time (Malusà et al., this volume). However, sedimentary successions exposed atop eclogitic rocks are rather uncommon, either because these sedimentary rocks are often buried beneath active sedimentary basins (e.g., in the young (U)HP belt of eastern Papua New Guinea), or because they have been largely eroded away and are no longer preserved e.g., in the Western Gneiss Region (Norway) and Dabie Shan

(China) (U)HP belts. In the Western Alps, the Tertiary Piedmont Basin includes the only syntectonic sedimentary successions resting directly atop the Eocene Eclogite Belt (Malusà et al., 2015, and references therein). In this perspective, the relationships between these sedimentary rocks and the underlying metamorphic units have been mapped in detail (at 1/10.000 scale) over an area of ~500 km2, in order to get an updated 1/50.000 geological map of this key area. This map provides new stratigraphic and structural constraints to the exhumation of the Eocene Eclogite Belt of the Western Alps and, more in general, to exhumation processes in modern and ancient orogenic settings. The study area, like other transects in the Western Alps, includes eclogitic units derived from subducted European continental crust (Valosio Unit), enveloped by eclogitized ophiolites (Voltri Unit), which are tectonically coupled along a synmetamorphic fault showing evidence of reactivation and fluid-rock interaction in the brittle field. These metamorphic units are unconformably covered by the transgressive Tertiary Piedmont succession, which shows major lateral variations both in lithofacies and thickness. The bottom of the Tertiary Piedmont succession encompasses the Molare Formation, that chiefly consists of Oligocene sandstones and conglomerates, locally including reef limestones attesting to extremely fast exhumation of the underlying Eocene eclogites, and their exposure close to sea level by that time. The Molare Fm is overlain by silty marls and fine sandstones (Rocchetta-Monesiglio Fm, lower Oligocene - Aquitanian), marls, glauconitic sandstones and biocalcarenites/biocalcirudites (Visone Fm, Burdigalian), and turbiditic sandstones (Cortemilia Fm, Burdigalian-Langhian), recording a complex Oligo-Miocene syntectonic deposition controlled by a network of strike-slip, reverse and normal faults that have been mapped in the field. These faults, often reactivating preexisting synexhumation faults, are marked by thick, continuous layers of cataclasites and fault breccias, and show the evidence of a polyphase evolution in the brittle field that is consistent with the information provided by associated sedimentary successions.

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Malusà, M.G., et al. (this volume), The stratigraphic key to (U)HP exhumation. Malusà, M.G., et al (2015), Contrasting styles of (U)HP rock exhumation along the Cenozoic Adria-Europe plate boundary (Western Alps, Calabria, Corsica), G3 doi: 10.1002/2015GC005767

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The stratigraphic key to (U)HP rock exhumation

Marco G. Malusà [a], Claudio Faccenna [b], Suzanne L. Baldwin [c], Paul G. Fitzgerald[c], Federico Rossetti [b]

a Dept of Earth and Environmental Sciences, Univ of Milano-Bicocca, Milan, Italy (marco.malusa@unimib.it)
b Department of Geological Sciences, University of Roma Tre, Italy
c Department of Earth Sciences, Syracuse University, New York, USA

The exhumation of (U)HP rocks remains one of the most exciting and controversial topics in Earth Sciences. Many different mechanisms have been proposed to explain how buoyant (U)HP rocks travel back to the surface following subduction to depths even >100 km. Here, we illustrate the contrasting stratigraphic records that might be expected for different (U)HP exhumation mechanisms, and provide examples of application from the Cenozoic Adria-Europe plate boundary.

In the case of fixed-boundary syn-convergent exhumation models (e.g., the channel-flow model), massive volumes of orogenic detritus are predicted to have been eroded from the accretionary wedge and deposited in sedimentary basins surrounding the orogen during (U)HP rock exhumation. This sediment includes HP clasts, and is accreted at the toe of the wedge as well as underplated. Recent attempts to apply syn-convergent exhumation models to the Western Alps (e.g., Jamieson and Beaumont, 2013) show that they are generally unable to reproduce the observed stratigraphic and petrologic evidence.

Alternative exhumation models, consistent with a stratigraphic record supportive of a minor role played by erosion, include mechanisms that invoke the motion of the upper plate away from the trench, as well as the retreat of the subduction hinge (slab rollback). Both of these mechanisms result in the removal of a tectonic lid, allowing for the exhumation of more buoyant rocks from HP or UHP depths.

When the upper plate moves away from the trench, the predicted geological response is for (U)HP rocks to be exhumed on the upper plate side of the orogen, at the rear of a lower pressure accretionary wedge. Sedimentary basins are starved during (U)HP exhumation. Synexhumation sediments are unconformably preserved on top of their basement on the lower plate side of the accretionary wedge, and do not include HP clasts. In the case of slab rollback, HP rocks are instead exhumed in the frontal part of the accretionary wedge, and show a younging trend towards the foreland. Synexhumation sediments, attesting to only minor orogenic erosion, lack HP clasts and are generally offscraped from their underlying basement (Malusà et al., 2015).

Exhumation triggered by the motion of the upper plate away from the trench is consistent with the geologic record preserved in the Western Alps. There, (U)HP continental eclogites were quickly exhumed up to the surface to be eventually covered by sediments, unlike predictions of synconvergent exhumation models. In comparison, the slab-rollback mechanism is documented along the Calabria transect, where HP rocks were exhumed from shallower depths and at lower rates during rollback of the Adriatic plate. Both of these mechanisms have been active at different times and in different places along the Corsica – Northern Apennines transect, where the western part of the accretionary wedge evolved in the Paleogene during European subduction, and the eastern part evolved in the Neogene during subduction and retreat of the Adriatic plate.

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Geometry of the basal thrust of the Dent Blanche (Western Alps): implications for the rheological behaviour of ultramafic rocks along the subduction interface.

Manzotti Paola [a], Ballèvre Michel [a]*

a Géosciences Rennes, UMR 6118CNRS, Université Rennes1, 35042 Rennes, France, paola.manzotti@univ-rennes1.fr

The Dent-Blanche klippe is the highest tectonic element in the Western Alps (for a recent review, see Manzotti et al., 2014). It is made of several superimposed slices, including (i) pieces of the lower continental crust (upper amphibolite to granulite facies rocks), (ii) upper continental crust (mainly granitoids of Permian age), and (iii) dismembered and folded remnants of a Mesozoic cover (Mont Dolin, Roisan Zone). Theses slices are bounded by mylonite zones, defining ductile shear zones at the scale of the klippe (e.g. the Roisan-Cignana Shear Zone, or the basal contact of the klippe).
A sequence essentially made of dismembered ophiolitic bodies, i.e. serpentinites, metagabbros, and metabasalts (prasinites), now found as lenses in a large amount of metasediments (calcschists), occurs below the Dent Blanche klippe. These derive from the Liguro-Piemontese basin, and are collectively referred as to the Tsaté nappe (part of the Combin Zone).
Much discussion has taken place on the tectonic relations between the Combin Zone and the overlying Dent Blanche klippe. The proposed geometries include (i) a folded tectonic boundary, allowing some material (e.g. serpentinites) of the Combin zone to be found inside the Dent Blanche (Stuz and Masson, 1938; Diehl et al. 1952; Roda and Zucali, 2011), and (ii) a serpentinite shear zone, which includes less deformed pods of oceanic (gabbroic) material and continentally-derived material (Arolla gneisses) (Angiboust et al., 2014), and (iii) a polypased ductile thrust at the contact between the two units (Kirst, 2014). A key element for these tectonic interpretations is the deformation behaviour of the ultramafic rocks.
Detailed mapping in a key area along the Combin – Dent Blanche boundary has been performed and will be illustrated using panoramic views and cross-sections. In addition, new whole-rock geochemical and mineral chemistry data have been acquired and will help to clarify the nature of the rocks involved in the Combin-Dent Blanche boundary. The reconstruction of the geometry, kinematics and P-T history of this major tectonic boundary will allow us discriminating between the different proposed models and emphasizes a counter-intuitive behaviour of the ultramafic rocks along the subduction interface.

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Constraining P-T conditions during thrusting of a higher-pressure unit over a lower-pressure one (Gran Paradiso Massif, Western Alps)

Manzotti Paola, Pitra Pavel, Ballèvre Michel

Géosciences Rennes, UMR 6118CNRS, Université Rennes1, 35042 Rennes, France, paola.manzotti@univ-rennes1.fr

The Money unit (Gran Paradiso Massif, Western Alps) crops out as a tectonic window below the Gran Paradiso unit. The Alpine evolution of these two units and of their tectonic contact has been achieved using a multidisciplinary approach that combines geological mapping (Manzotti et al., 2014), meso- and micro-structural analysis and pseudosection calculations. In both units, four stages of deformation and metamorphism have been identified.
Stage 1 reflects the phase of continental crust subduction. P-T conditions of 18-20 kbar 480-520 °C and of 13-18 kbar, 500-530 °C have been estimated for the Gran Paradiso and the Money units, respectively (Fig. 1). Difficulties in modelling properly the Si content of muscovite explain the rather large uncertainties still present on the estimated peak pressure. However, a maximum difference of ~20 km in the depth reached by these two units during the early Alpine history may be suggested.
During stage 2 the Gran Paradiso unit was thrust over the Money unit at about 12.5-14.5 kbar and 530-560 °C, in the albite stability field (Fig. 1). The thrust contact was folded during stage 3 together with the entire Money unit, while both units were exhumed together (stage 4). During this polyphase evolution, detrital garnets (Manzotti and Ballèvre, 2013) have been partially dissolved, while the earliest Na-bearing phases (glaucophane, paragonite) have been overprinted by the low pressure mineral

associations.

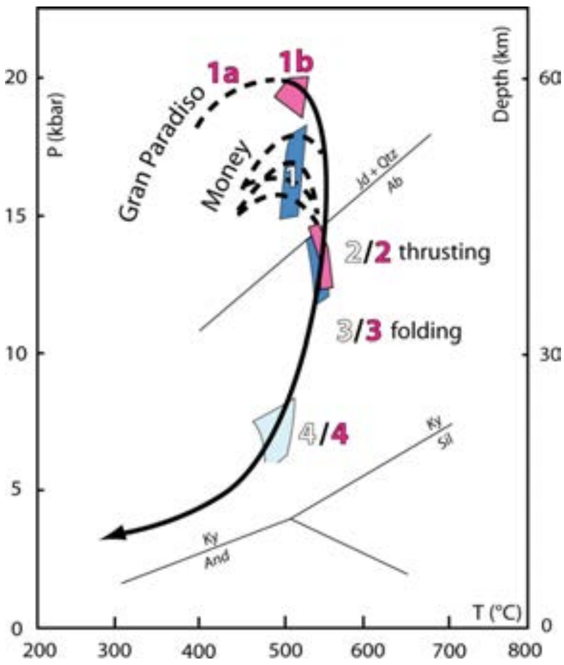

Figure 1: P-T paths for the Gran Paradiso and the Money units as inferred from garnet-chloritoid micaschist and quartz-pebble meta-conglomerate. Dark blue and pink fields delimit P-T conditions of stages 1 and 2 for the Money and the Gran Paradiso unit respectively.

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How to simplify geological maps? Examples in Valais and Chablais (Swiss and French Alps)

Michel Marthaler

University of Lausanne

To simplify a geological map (at the level of the 1: 50 000 and 1: 25 000) is a complicated process. The map, the legend, the tectonic draft, cross section and the text of the note explicative contain incomprehensible terms and concepts for the general public.
Several significances hide behind the colors : Time initially, but also groups of rocks which are born in their paleoenvironments. Tectonics tells another story, it adds a second stacking of rocks which are the nappes. Lastly, there are signs and the pastel colors of the Quaternary. It is not so simple to make comprehensible, that these last deposits due to erosion come to hide the underlying rocks (on the map as on the field).

This talk would like to show two concrete achievements of geological maps to bring the amateurs, the teachers and the guides in mountain to understand and use all the wealth of a geological map. Simplified, these maps can become a main door (rather than a scarecrow) in the world of earth sciences.

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Apparent Polar Wander Path for Adria extended by new Jurassic paleomagnetic results directly from its stable core: tectonic implications

Emő Márton[a], Dario Zampieri[b], Vlasta Ćosović[c], Alan Moro[c], Roberta Romano[b]

a Geological and Geophysical Institute of Hungary, Palaeomagnetic Laboratory, Columbus 17-23, H-1145 Budapest, Hungary, paleo@mfgi.hu
b Department of Geosciences, Univ Padova, , Italy,
c Department of Geology, Faculty of Sciences, University of Zagreb,

As a continuation of a systematic paleomagnetic research in the northern part of stable Adria, which provided a well-defined APW for the Cretaceous-Eocene, we present new paleomagnetic results for the Jurassic. They were obtained from 15 geographically distributed localities of the Trento platform. The paleomagnetic directions were defined as a result of standard laboratory processing, component analysis and statistical evaluation of 175 independently oriented drill cores. The Early Jurassic shallow water carbonates are characterized by highly consistent declinations but scattered inclinations. In contrast, tightly grouping overall-mean paleomagnetic directions were obtained for both, the Lower and Upper members of the Rosso Ammonitico Veronese formation, which are of Middle and Late Jurassic age, respectively. The available sporadic observations from Apulia (the southern part of stable Adria) are in agreement with coeval Cretaceous data for the northern part of stable Adria, while the younger ones differ. In order to exclude the possibility of remagnetization of the Cenozoic paleomagnetic directions in Apulia, results with positive fold tests should be obtained from that area.
The declinations calculated for stable Adria from any of the published African APWs exhibit systematically less CCW rotation than the ones measured for Adria. This suggests that Adria definitely decoupled from Africa, according to our interpretation at the end of Cretaceous, and rotated again with respect to Africa after the Eocene. It is also important to note that the direct APW for Adria is better constrained for timing of important changes, like the speed and the sense of rotations than the APWs for Africa. This is particularly true for the 163-107 Ma interval, for which our results imply CW rotation and southward shift up to 155 Ma, followed by CCW rotation and northward shift, which can be connected to the opening and initial closing of the Neo-Tethys.

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Hyper-extension along rift systems: structural and sedimentary implications for their formation and deformation

Masini, Emmanuel[1]; Manatschal, Gianreto[2]; Tugend, Julie[2]; Mohn, Geoffroy[3]; Kusznir, Nicholas[4] & Unternehr Patrick[1]

1 Total EP, avenue Larribau, F-64000 Pau, France
2 IPGS, 1, rue Blessig, F-67084, Strasbourg, France
3 Université de Cergy-Pontoise, F-95000, France
4 University of Liverpool, Liverpool L69 3GP, UK

The discovery of hyper-extended domains in deep-water rifted margins challenged the classical view of how rift basins evolve before oceanic accretion. Along distal domains of margins, rift basins develop over hyper-thinned crust (<15km thick) and even above exhumed subcontinental mantle. Academic and industrial studies performed on off- and on-shore examples show that long offset detachment faulting has a key role to form these frontier sedimentary basins. Despite their apparent widespread occurrence along rifted margins, impacts of hyper-extension on tectono-sedimentary processes, the thermal and fluid histories also impacting hydrocarbon prospectivity are still poorly constrained.
In this presentation, we review and compare key multi-scale observations from 2 fossil analogues of hyper-extended rift systems.
The first example, in the Western Pyrenees, corresponds to an asymmetric hyper-extended rift system that failed to break-up and that can be investigated on the field and by subsurface data.
The second example in the Alps, gives the access to supra-detachment sedimentary evolution linked to mantle exhumation.
Based on these studies and by comparison to offshore data, we conclude that detachment systems can develop a preferential orientation (a polarity) from the crustal necking zones toward Ocean Continent Transition. In- and out-of-sequence supra-detachment basins develop successively following migration of deformation (a bit like piggy-back basins in orogenic settings) and has fundamental implications such as:
The "syn-rift deposits" can be alternatively pre-, syn-, and post-tectonics along margins (diachronous syn-tectonic deposits).
Hyper-extension processes implies the development of so-called "sag basins" that are different along upper and lower plate margins. The former is an true sag basin implied by the isochronous post-tectonic subsidence of necking zone areas whereas the second is implied by sequential inactivation of supra-detachment basins.
Hyper-extension along margins are not only controlling their first order architecture, but also drives their inversion during convergence as inheritances. Taking the advantage of a preserved analogue of hyper-extended rift system in the Western Pyrenees, we performed an observation-based kinematic model that aim to reproduce an hyper-extended rift system that is further inverted into a collisional orogen.

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Preserved organic matter in the Alpine Ocean Continental Transition (Totalp)

Tsvetomila Mateeva[1], Nick Kusznir[1], George Wolff[1], John Wheeler[1] and Gianreto Manatschal[2]

1Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, L69 3BX, UK 2CNRS-EOST, Université de Strasbourg, 1 rue Blessig, F-67084 Strasbourg, France

Evidence from ocean ridge drilling and dredging and from the exhumed Tethyan continental margin in the Alps demonstrates that mantle serpentinization, a process deriving from the interaction of mantle rock and water, occurs at slow-spreading ocean ridges and magma-poor rifted continental margins. Observations at white smokers in modern ocean settings suggest that methane produced by serpentinization can support methanotrophic bio-systems, a system that uses methane as its only source of carbon and energy.
An important question is whether such bio-systems are more generally pervasive in their association with serpentinized mantle in the subsurface. This has important global implications for the importance of the hidden sub-surface bio-systems, the fate of methane and the carbon cycle. We examine whether serpentinized exhumed mantle at magma-poor rifted continental margins shows evidence for such a methanotrophic system.
The Totalp unit in the eastern Swiss Alps has been chosen for an initial study to investigate the presence or absence of methanotrophic biosystem within serpentinized exhumed mantle in the Alpine Tethyan margin. Totalp has undergone little Alpine deformation and only low grade metamorphism. Hands specimens and cores have been taken from the Totalp area in order to sample serpentinization and its lithological diversity in the search for presence or absence of biomarkers. Thin sections analysis reveals multiple serpentinization events. XRD analysis shows complete serpentinization of the olivines and orthopyroxenes.
The majority of the samples contain hydrocarbons in the form of n-alkanes in the range C20 - C32. Some sediments contain isoprenoids, for example pristane and phytane. The organic molecular distribution is consistent with the temperature history of the basin. Totalp samples are characterized by carbon contents of 0.03% to 12.90% and organic carbon contents of 0.10% to 1.90%. This large range of values reflects the large lithological diversity of this area.
First results from Totalp show evidence for preservation of marine organic matter in the serpentinized mantle and overlying sediments of the ancient Tethyan OCT. More work is required to understand whether any of the organic matter is generated from methanotrophic bio-systems, and

if so whether the methane originated from an organic or inorganic source. This will require compound specific isotopic analysis of the carbon in the isoprenoids.

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New Lu-Hf ages from the eclogite type-locality in the Eastern Alps (Grünburgerbach, Saualpe and Hohl, Koralpe)

Miladinova, Irena[1], Froitzheim, Nikolaus[1], Nagel, Thorsten[2], Münker, Carsten[3]

1 Steinmann-Institut, Universität Bonn, Poppelsdorfer Schloss, D-53115 Bonn, Germany (irenamil@uni-bonn.de; niko.froitzheim@uni-bonn.de)
2 Department of Geoscience, Aarhus University, Høegh-Guldbergs Gade 2, 8000 Aarhus, Denmark (thorsten.nagel@geo.au.dk)
3 Institut für Geologie und Mineralogie, Universität zu Köln, Zülpicher Strasse 49b, D-50674 Köln, Germany (c.muenker@uni-koeln.de)

The Koralpe-Saualpe region is the largest region in the Eastern Alps exposing high-pressure metamorphic rocks form the Cretaceous Eo-Alpine orogenic event and contains the type locality for eclogite (Hauy, 1822). The Koralpe and Saualpe complexes also expose the Variascan metamorphic basement of the Lower Central Austroalpine. The grade of the Cretaceous metamorphism in the Eastern Alps increases to the southeast, with maximum pressures and temperatures reaching up to 3.5 GPa and 850 °C in the Pohorje Mountains (Janak et al., 2015). Here we present new Lu-Hf isotopic data from eclogites from the Hohl locality in the southern Koralpe (1) and from the Grünburgerbach locality in the southern Saualpe complex (2) in the Eastern Alps. Two-point isochrones from samples of both localities based on one whole rock and one garnet separate yield an age of 100.1 ± 1.4 Ma and 99.2 ± 1.1 Ma, respectively. The garnets in the eclogite from Hohl display a homogenous composition with no zoning of major elements, whereas the garnets of the samples from Grünburgerbach shows an enrichment of Mn in the cores and lower contents towards the rims, which indicates prograde garnet growth during increasing P and T.
This new Lu-Hf garnet age data for the timing of the eclogite-facies metamorphism within the rocks of Saualpe and Koralpe units displays slightly older ages than the Lu-Hf garnet age data from the Pohorje Mountains in Slovenia (96 Ma; Sandmann et al. 2011), which constraints the peak metamorphic conditions to Cenomanian times.

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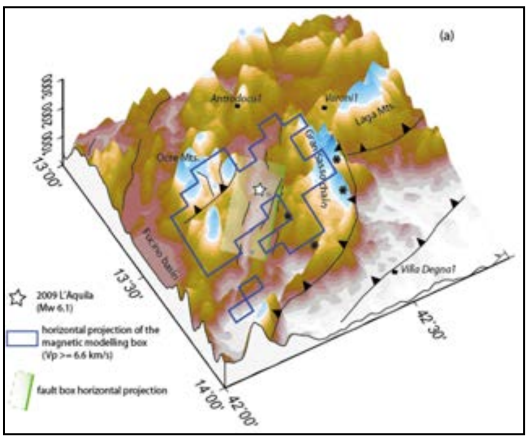
Crustal setting of the Apennines from joint inversion of seismic tomography and magnetic anomaly data: Evidence from L'Aquila fault zone (Italy)

Liliana Minelli, Fabio Speranza

Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, liliana.minelli@ingv.it

High-resolution tomography from the 2009 L'Aquila extensional seismic sequence has shown that the Mw 6.1 main shock and most of the aftershocks occurred within a high velocity body (6.6≤Vp≤6.8 Km/s), located between depths of 3 and 12 km (Di Stefano et al., 2009). The nature of the high Vp-body has remained speculative because the Vp velocities are compatible with different lithologies: exhumed mafic lower crustal rocks, hydrated mantle rocks (serpentinites), or dolomites. We used 3D magnetic anomaly modelling to investigate the nature of the L'Aquila body and the deep crustal setting in the central Apennines (Fig. 1). The modelling does not support serpentinites (30-50% serpentinization degree) and gabbros as possible sources of the seismic wave high-velocity body. Accordingly, we conclude that the high Vp-body may represent non-magnetic upper Triassic and possibly lower Liassic dolomites that have been drilled in neighbouring wells for 2-4 km. This conclusion is also consistent with the lack of a coherent gravity anomaly for the body. We speculate that ultra-thick Triassic dolomites, reaching a thickness of 8 km, may have been deposited either in the hanging-wall of Triassic normal faults or in releasing bends of strike-slip faults. In either case, strong mid-late Triassic tectonics is needed to provide the thick dolomite pile and the significantly thickness change across the L'Aquila fault (Speranza and Minelli, 2014). Triassic faults controlling dolomite deposition may have been reactivated later as high-angle thrust ramps during the latest mid-Pliocene Apennine compressive episodes, and finally as normal faults during the Pleistocene-to-present-day extensional tectonics.



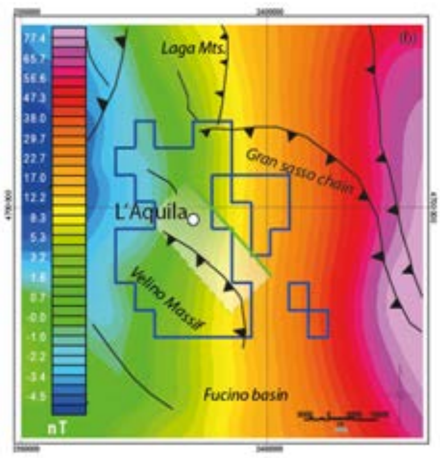


Figure 1 – a) Digital elevation model and main tectonic feature of the central Apennines; b) Aeromagnetic map of the L'Aquila area reduced to an altitude of 2500 m a.s.l..

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Late Eocene – recent tectonic evolution of the northern Internal Dinarides (western Serbia)

Mladenović Ana, Trivić Branislav, Cvetković Vladica, Pavlović Radmila

University of Belgrade – Faculty of Mining and Geology, Đušina 7, Belgrade, Serbia; ana.mladenovic@rgf.bg.ac.rs

The Internal Dinarides represent the most distal part of the deformed Adriatic margin, situated near the complex suture zone, which runs through the central line of the Balkan Peninsula. Present tectonic pattern of this area is a result of Late Cretaceous subduction and closure of the Neotethys Ocean and subsequent Cenozoic collisional and post-collisional processes. Since the Late Miocene, the most important factor controlling neotectonic processes has been the counterclockwise rotation and northward motion of the Adriatic microplate in respect to the Dinaric orogen. In the northern part of the Internal Dinarides, this tectonic process is manifested through moderate but constant seismic activity, where most of the seismic energy is released along well-known fault systems, active also in the neotectonic period. However, although this area belongs to the one of seismically most active areas within the Internal Dinarides, Cenozoic brittle fault kinematics is poorly documented and remains almost completely unknown.

In this research we performed a calculation of tectonic stress tensors in order to determine brittle tectonic regimes acting in this area during the Cenozoic times, as well as their relative chronology. Two types of tectonic stress tensors have been calculated: paleostress tensors, based on the inversion of fault slip data, and recent stress tensor, based on the inversion of focal mechanisms of earthquakes. Fault slip data have been collected within the geological units of different age and lithology: Permian, Triassic and Cretaceous limestones, Jurassic peridotites and serpentinites, and Miocene marls and marly limestones. Determination of the slip sense on the fault planes was done using slip criteria marked as Young Geological Data of the World Stress Map project. The most common slip indicators observed on fault planes were calcite and magnesite fibers, cataclastic lineation, gouging-grain grooves and "carrot-shaped" markings. The relative chronology of brittle structures was determined using criteria of cross-cutting relationships of faults and striations, fracture mineralization and structural features of the brittle overprint of rocks. Focal mechanisms have been calculated based on the first motion of P-waves for earthquakes with magnitude higher than 3.5. Inversion of groups of focal mechanisms was performed in order to define tectonic stress tensor currently active in this area.

Four brittle deformation phases were distinguished. Phase D1 is characterized by NNW – SSE contraction, most possibly related to the westward propagation of thrusting of the Dinaric orogenic wedge over the Adriatic platform. N – S compression indicated by thrust faulting of NE- and NW-trending faults represent phase D2. This phase is a result of Oligocene shortening of the Dinaric orogenic wedge and is most likely correlated with Oligocene post-collisional magmatism of this area. Deformation phase D3 is regarded as extensional phase. It is characterized by NE – SW extension, comprising early Miocene opening of the Dinaridic intra-mountain basins. Deformational phase D4a is represented by NW – SE (orogen parallel) extension, and is most likely a result of late Early Miocene to early Late Miocene lake sedimentary cycle in Dinarides and regional extension that caused formation of metamorphic core complexes within the Internal Dinarides. The youngest strike-slip deformation phase D4b is indicated by sinistral faulting along generally E-trending faults and dextral faulting along N-trending faults. This deformation phase is characterized by NNE – SSW oriented compressional axis. This strike-slip phase is also recently active, which is documented by the stress tensor calculated based on the focal mechanisms of earthquakes. This stress tensor indicates that, apart from the regional stress derived by Adria push mechanism, seismicity in this area is also controlled by local factors.

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The International AlpArray Initiative - Aiming at Profound Understanding of Alpine Orogeny and Geodynamics

Molinari, Irene[1]; Hetényi, György[2]; Clinton, John[2]; Kissling, Edi[1]

1 Institute of Geophysics, ETH Zurich, Switzerland;
2 Schweiz. Erdbebendienst (SED), Zurich, Switzerland

The international AlpArray initiative starts in 2015 with the aim to unravel the dynamics, at different scales, of the greater Alpine-Mediterranean orogenic system, adopting a multidisciplinary approach. The project gathers different national efforts and instrument pools into a trans-national collaboration including data acquisition, processing and imaging. A large number of institutes, universities and observatories have already joined the AlpArray scientific project. We will describe the current state of the project, in terms of seismic network, experiments, and science plans.
The various data recorded during AlpArray project --- seismic, gravity, GPS, magnetotellurics, geological studies--- will fundamentally improve the current state of knowledge and interpretation of the geodynamical processes that take place in this area. In particular, the high quality seismic data recorded by the AlpArray Seismic Network with more than 500 broadband seismometers (260 of them are temporary stations deployed during the project) combined with the most recent imaging techniques, will provide 3D high resolution mapping of structures and physical properties of rock volumes.
The AlpArray region has been the target of a greater set of geophysical and geological studies, exploiting various geophysical techniques. Local earthquake tomography (e.g. Di Stefano et al, 2009), P-wave tomography (e.g. Lippitsch et al., 2003; Diehl et al., 2009; Gualtieri et al., 2014), active reflection and refraction seismic experiments (e.g. Guterch et al., 2005), receiver functions (e.g. Kummerow et al. 2004), combinations of such data (e.g. Spada et al., 2011) and large scale compilation studies (e.g. Molinari&Morelli, 2011) have contributed to obtain better images of the crustal and the upper mantle structure, increasing our understanding of orogenic processes. However, the slabs' geometry, their internal properties, slab-tears and crust-mantle interface, particularly in the transitional areas between the Alps and adjacent orogens (e.g. Apennines), are still insufficiently known. Moreover, a consensus 3D high resolution crustal model for the whole region is still missing.
We focus here our attention mainly on the Alpine and circum Po Plain crustal structure and we present our recent findings from seismic noise surface wave tomography. We will discuss in details the scientific questions and open problems we aim to explore with the new AlpArray seismic dataset.

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Key role of Upper Mantle rocks in Alpine type orogens: recipes for rift, serpentinization and subduction zone processes

Müntener, Othmar

Institute of Earth Sciences, University of Lausanne, CH 1015 Lausanne, Switzerland, email: othmar.muntener@unil.ch

Mantle peridotites and their serpentinized counterparts from ocean-continent transition zones (OCT's) and (ultra-) slow spreading ridges question a series of 'common beliefs' that have been applied to understand Alpine-type collisional orogens in the framework of the ophiolite concept. Among these are: (i) the commonly held assumption of a simple genetic link between mantle melting and mafic (MORB-type) magmatism, (ii) the commonly held assumption that mélange zones represent deep subduction zone processes at the plate interface, (iii) that pre-collisional continental crust and oceanic crust can easily be reconstructed and used for reconstructions of the size of small subducted oceanic basins, and (iv) formation of a continuous sheet of mafic oceanic crust - the lack of mafic rocks results in a lack of 'eclogitization potential' and hence a lack of potential for subduction initiation and subsequent slab pull during convergence. In this presentation, we provide a synopsis of mantle rocks from the European realm to show that inherited mantle signatures from previous orogenies play a key role for the interpretation of ophiolites, and that peridotites from present-day passive margins show striking similarities to the metamorphic equivalents in Alpine type orogens.
Field data and petrology demonstrates that ancient, thermally undisturbed, pyroxenite-veined subcontinental mantle formed parts of the ocean floor next to thinned continental crust. These heterogeneities might comprise an ancient subduction component. Mantle upwelling and decompression melting during rifting forms partial melts that enter a thick conductive lithospheric mantle and inevitably leads to freezing of the melt and refertilization of the lithospheric mantle. This process might well be at the origin of the difference between magma-poor and volcanic margins. Mafic bodies (gabbros, basalts) are small and discontinous. The abundance of plagioclase

peridotites in the Alpine ophiolites are interpreted as recorders of refertilization processes related to thinning and exhumation of mantle lithosphere. Similar features are found at slow to ultra-slow spreading ridges where the thermal boundary layer (TBM) is thick and extension is variably accommodated by magmatism and tectonism. Another important result is the discovery of extremely refractory Nd-isotopic compositions with highly radiogenic 147Sm/144Nd, which indicates that partial melting processes and Jurassic magmatism in the Western Tethys are locally decoupled. Although the isotopic variability might be explained by mantle heterogeneities, an alternative is that these depleted domains represent snapshots of melting processes that are related to Permian and/or even older crust forming processes. The findings of such refractory mantle rocks in the Western Alpine arc and the similarity in model ages of depletion suggests a connection to the Early Permian magmatic activity. Shallow and deep crustal magmatism in the Permian is widespread over Western Europe and the distribution of these mafic rocks and associated depleted mantle are likely to pre-determine the future areas of crustal thinning and exhumation during formation of the Tethyan passive margins. If the dimensions of mantle exhumation and the formation of proto-oceanic crust (refertilized domains) can be compared to the Iberia-Newfoundland or the Australian - Antartic margins, then there is little room for true oceanic crust in the Ligurian Tethys. Possible consequences will be discussed.

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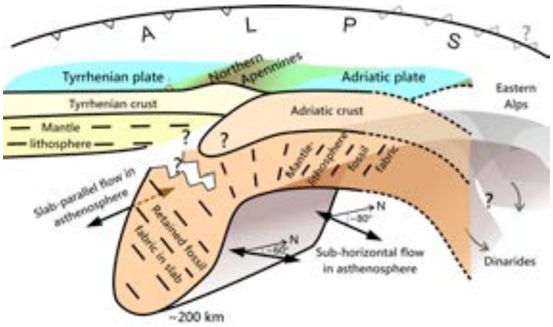
Fabrics of the upper mantle and the lithosphere-asthenosphere boundary beneath the Northern Apennines

Munzarova, Helena; Plomerova, Jaroslava; Babuska, Vladislav; Vecsey, Ludek

Institute of Geophysics, Academy of Sciences of the Czech Republic, Bocni II/1401, 141 31, Prague 4, Czech Republic
helena@ig.cas.cz

Evolution of the Northern Apennines has been controlled by processes of syn-convergent extension related to a roll-back of the Adriatic slab and to an extension of the Tyrrhenian back-arc basin, all driven by the slow collision of the African and European plates. We image anisotropic structure of the upper mantle beneath the Northern Apennines by analyzing teleseismic body-wave anisotropy evaluated from data collected during experiment RETREAT (2003-2006; Margheriti et al., 2006).
Joint analysis of anisotropic parameters evaluated from two independent data sets – teleseismic P-wave travel times and shear-wave splitting – allows us to identify regions of different fabrics (Plomerova et al., 2006; Munzarova et al., 2013). We recognize three main regions – the Tyrrhenian, Adriatic and Transition in between. Each of these regions is characterized by its own anisotropic pattern resulting from oriented fabrics both in the mantle lithosphere and in the sub-lithospheric mantle. Beneath the thin Tyrrhenian plate, a slab-parallel flow prevails in the sub-lithospheric mantle, while nearly slab-perpendicular high velocities dominate on the other side of the region, beneath the thicker Adriatic plate. This asthenospheric-flow pattern excludes a simple corner-flow model that would fit the fabric of the upper mantle in the syn-convergent extensional tectonics and thus suggests the end of the subduction roll-back. Two domains of the continental Adriatic lithosphere are characterized by their own fossil fabric with inclined symmetry axes.
We also present a model of lithosphere-asthenosphere boundary (LAB) in the Northern Apennine region derived from careful azimuthal analysis of the static terms of the relative P-wave travel-time residuals. We estimate the lithosphere thickness of the Tyrrhenian and Adriatic plates at ~50 km and ~80 km, respectively, the latter being subducted down to no more than ~200 km with indications of inherited frozen-in anisotropic fabric. The overall upper mantle fabric in the region indicates that if a potential detachment at the Northern Apennine slab exists then it would have to be narrow and in its initial stage.



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Extension-rate dependent rift architecture in 3D analogue models: insights for Alpine-type orogens

Nestola Yago, Storti Fabrizio, and Cavozzi Cristian.

Parco Area delle Scienze 157/a - Parma – Università di Parma – yago.nestola@unipr.it

Alpine-type orogens are interpreted as result from the collision of former rifted margins. Recent studies showed that the rift-architecture inheritance could play a critical role in controlling the 4D evolution of Alpine-type orogens. In this framework, differences of inversion modes between the internal and external zones of the Western Alps can be related to the pre-orogenic rift-related domains (e.g. Mohn et al., 2014). The external zone is affected by mild reactivation of the former proximal margin domain, where the crustal thickness was about 30km. On the other hand, the internal zone results from the reactivation of the former distal margin domain, characterized by less than 10km crustal thickness. This caused the stacking of a complex pile of pre- and syn-rift sequences against the 'necking zone', that is the locus where the lithosphere dramatically thins. The 'necking zone' separates the proximal and distal domains and acts as a buttress for shortening. Indeed, both rift architecture and shape of necking play a fundamental role in the building up of an Alpine-type orogen. In this study, we use analogue modeling to investigate the role of extension-rate in rift-architecture. We simulated an ideal 4-layer lithosphere where brittle and ductile crustal layers rest on top of brittle and ductile mantle layers. The entire experimental lithosphere floats over a fluid analogue of the asthenosphere. Models were deformed pulling apart a mobile wall of the sandbox that confined the experimental lithosphere. We investigated three different extensional velocities, spanning one-order of magnitude, specifically 5, 10, and 50mm/h (equivalent to 2, 4, and 20mm/y in natural prototypes). The finite extension of the models is 5cm (75km): 2.5 times the thickness of the crust. Coupled top-bottom laser-scanner devices monitored the evolution of the models (Nestola et al., 2013).

At the end of deformation, rift architectures show severe differences as a function of extension-rates, at both crustal and lithospheric scales. In particular, at lithospheric scales, localized necking occurred at low extension-rates, while a more distributed deformation happened with increasing the extensional velocity. Eventually the faster strain rates caused the nucleation of second-order necking.

At crustal scale, well-developed and localized necking zones formed for low and intermediate extension-rates, while thinning occurred over a wide cross-sectional length in high-velocity models (Nestola et al., 2014). Based on the results of our experimental programme, we infer that the inherited rift architectures that have been described in the Western Alps as the locus of major buttressing during the orogenic stage (e.g. Mohn et al., 2014), were likely produced at intermediate to low extensional velocities.

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Present-day uplift of the Western Alps

J.-M. Nocquet[1], C. Sue[2], A. Walpersdorf[3], T. Tran[4], N. Lenôtre[4], P. Vernant[5], M. Cushing[6], F. Jouanne[7], F. Masson[8], S. Baize[6], J. Chéry[5], P. Van der Beek[3] and the RENAG Team

1 Geoazur IRD, Univ. Nice Sophia-Antipolis, France
2 Université de Franche-Comté, Besançon, france.
3 ISTerre – Université Grenoble-Alpes – CNRS, Grenoble, France
4 IGN France
5 Geosciences Montpellier, , University of Montpellier, France.
6 IRSN BP 17, 92262 Fontenay-aux-Roses Cedex, France
7 ISTerre – Université Savoie-Mont-Blanc, Chambéry, France
8 EOPGS Strabourg, france

Collisional mountain belts grow as a consequence of continental plate convergence and eventually die under the combined effects of gravitational collapse and erosion. Using a decade of GPS data, we show that the western Alps is a belt with zero horizontal present-day kinematics boundary conditions, offering the opportunity to investigate the orogen evolution at the transition between the two phases. We find no significant horizontal motion within the belt, but GPS and levelling measurements independently indicate a regional pattern of uplift reaching ~2.5 mm/yr in the northwestern Alps. We investigate the contributions of erosion and glacial isostatic adjustments, but conclude that their summed effects explain at most 60% of the observed uplift rates. Therefore, rock uplift rates exceed erosion rates and the average surface height in the northwestern Alps is presently increasing. In the absence of convergence, surface uplift must result from deep-seated processes.

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The use of biostratigraphic tools in dating the Voirons Flysch (Gurnigel Nappe, Haute-Savoie, France)

Lina M. Ospina-Ostios[1], Jérémy Ragusa[2], & Pascal Kindler[2]

1 Universidad del Valle (Colombia)
lina.ospina.o@correounivalle.edu.co
2 Section of Earth and Environmental Sciences, University of Geneva, Switzerland

The Gurnigel nappe had been studied in detail for many years. Nonetheless, because their complexity some questions still remain misunderstood. These questions are closely related to their paleogeographic origin and the mechanism which let this nappe to be at their present location. The current answer to these questions is based in the age found for these sediments. For this kind of deposits, this age depend on test preservation of microfossils in marly intervals. Observations of the latter feature combined with the use of the well know stratigraphic ranges make it possible to identify the presence of reworked forms in the assemblages; and thus to identify the magnitude and range of reworked material.

To date this nappe, nannoplankton and dinoflagellates, as well as benthic foraminifera dating has been used by previous authors; concluding that this nappe has a Late Cretaceous to lower Middle Eocene age. To determine more precisely the age of Gurnigel nappe at the Voirons Massif we have revisited some of the "well-known" geological sections, we have dated the planktonic foraminifers' content of pelagic shales. New age determinations were obtained for all the exposures studied. In some sites providing important results (like Moutonnières and Bons exposures), the marly levels were dated up to three times. Our results suggest that, the Gurnigel Nappe at the Voirons Massif is late Middle Eocene to Late Eocene. We also found that is not possible to repeat results from a specific shale level. The latter suggest the high lateral variation is also present in the foraminiferal content. However, calcareous nannofossil and dinoagellate assemblages obtained from some of these samples produced an older age. We are aware that in some flysch-type formations equivalent ages have been obtained both with planktonic foraminifera and calcareous nannoplankton (Piguet, 2000; Callec, 2001), and in other regions, calcareous nannofossil biostratigraphy have provided more reliable results compared to planktonic one (Catanzariti et al., 2009). Probably these diferences are strongly related to the chosen method. These results implicate that to dating flysch sediments is more delicate than suspected and make necessary to take in to account their lateral variation in foraminifers' content.

We would like to thank Professor Roland Wernli (University of Geneva) for his planktonic foraminifera determinations and much helpful advices.

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Early Miocene (Ottnangian) Environmental Crisis in the Lower Austrian Molasse Basin: A key to the tectonic evolution of the Eastern Alps – Molasse basin system

Palzer Markus[1], Knierzinger Wolfgang[1], Wagreich Michael[1], Meszar Maria E.[1], Gier Susanne[1], Soliman Ali[2], Kallanxhi Mădălina -Elena[3]

1- Department of Geodynamics and Sedimentology, University of Vienna, Austria (a0821104@unet.univie.ac.at)
2- Geology Department, Tanta University, Tanta, Egypt
3- Department of Geology, Babeş-Bolyai University, M. Kogălniceanu 1, Cluj-Napoca 400084, Romania

In the Early Miocene (late Ottnangian), a global sea level drop and the continuous rise of the Alps led to the regression of the Paratethys sea. In the Lower Austrian Molasse Basin, this event is represented by yellowish-brownish to greyish white mica-rich and carbonate-free sands and silts with clayish interlayers, formerly called Oncophora Beds, now called Traisen-Formation (TF) (Pixendorf Group). Drill cores from OMV-wells predominantly from the NE show hundreds of meters thick sequences of pelites with intersections of sands interpreted as representing this time interval. Contrary to the mainly brackish TF, a turbiditic and predominantly fully marine deep-water environment is inferred. Based on a detailed well section, this sandy deep-water interval of the former Oncophora Beds is renamed as Wildendürnbach Member (WM).
An OMV-funded project investigates the relationship between these sediments, their provenance, facies and stratigraphical and chronological range. Mineralogical investigations (XRD, thin section, microprobe) show homogeneous compositions of sands and pelites. Therefore large variations of the source rocks seem unlikely. Whole rock chemistry, carbonate content measurements and biostratigraphic investigations on samples from the WDK4 and Schaubing wells indicate a prominent interval of carbonate and (low-)salinity crisis. B/Al* ratios and TOC/S proxies indicate an interval of lowered salinities largely barren of fossils. It starts at the top of the so called "Fischfazies" or "Meletta Schlier", a distinct pelitic fossiliferous interval of Eggenburgian age. In addition, an increase and compositional change of clastic input is present at the onset of the salinity crisis interval (e.g. rising mica contents, rising Mn-contents, lowered Sr-contents…). The marked increase in clastic input at the onset together with the changing environmental conditions may indicate a tectonic event in the Alpine hinterland. We speculate that rapid uplift of the eastern part of the Northern Calcareous Alps removed overlying gravel (Augenstein Formation) and caused the closure of the Molasse seaway ("Amstetten Swell") thus influencing provenance and Paratethys seawater chemistry.

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Seismic imaging of the subduction complex of the Western Alps

A. Paul[1], L. Zhao[2], S. Guillot[1], M. Malusa[3], S. Schwartz[1], T.Dumont[1], S. Solarino[4], and CIFALPS Team

1 ISTerre, University of Grenoble & CNRS, BP 53, 38041 Grenoble, anne.paul@ujf-grenoble.fr
2 Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
3 University of Milano-Bicocca, Milan, Italy
4 INGV, Genova,Italy

The first conclusive evidence in support of the burial (and exhumation) of continental crust to depths larger than 90 km was provided by the discovery of coesite-bearing

metamorphic rocks in the Dora Maira massif of the Western Alps (Chopin, 1984). However, the greatest depth ever recorded by geophysical means for the European Moho in the Western Alps is 55 km by wide-angle seismic reflection (ECORS-CROP DSS Group, 1989).
In an effort to image the European Moho at greater depth, and unravel the very complex lithospheric structure of the Western Alps, we have installed the CIFALPS temporary seismic array across the Southwestern Alps for 14 months (2012-2013). The almost linear array runs from the Rhône valley (France) to the Po plain (Italy) across the Dora Maira massif where exhumed HP/UHP metamorphic rocks of continental origin were first discovered. We used the receiver function technique that enhances P-to-S converted waves at velocity boundaries beneath the array from records of earthquakes at teleseismic distances. After careful migration and stacking using a convenient crustal velocity model, the receiver function records provide a depth section that displays the main crustal structural boundaries beneath the profile.
Beneath the Southeast basin and the external zones, the seismic section displays a clear converted phase on the European Moho, dipping gently to the ENE from ~35 km at the western end of the profile, to ~40 km beneath the Frontal Penninic thrust (FPT). The Moho dip then noticeably increases beneath the internal zones, while the amplitude of the converted phase weakens. The weak European Moho signal may be traced to 75-80 km depth beneath the eastern Dora Maira massif and the westernmost Po plain. At shallower level (20-40 km), we observe a set of strong amplitude negative-polarity converted phases (generated by downward velocity decreases) beneath the Dora Maira massif and the westernmost Po plain. Records in the Po plain display a strong but intricate converted signal from the Adria Moho between 10 and 35 km depth.
We propose that the negative-polarity converted phases are generated by downward decreasing velocity between, from top to bottom, the Ivrea body of mantle origin, a thick wedge of HP/UHP metamorphic rocks and the European lower crust. Our receiver-function section thus displays the classical wedge-shaped image of the Alpine crust, but with the deepest European Moho ever recorded (75-80 km), and clear evidence of continental subduction of the European lower crust beneath the Ivrea mantle body (and possibly Adria mantle) as a negative-polarity converted phase indicative of an inverted Moho. Based on our seismic section, complemented with seismic and gravity modelling and geological arguments, we propose a new crustal-scale cross-section of the Western Alps.

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Transpressional faulting along the western border of the Lanzo Ultramafic Complex (italian Western Alps)

Perrone Gianluigi[1], Cadoppi Paola[1,2], Tallone Sergio[3], Bacenetti Marco[1]

1 Department of Earth Sciences - University of Turin, Via Valperga Caluso, 35 – 10024 Torino (Italy); gianluigi.perrone@unito.it
2 Research Centre on Natural Risks in Mountain and Hilly Enviroments (NatRisk) - University of Turin
3 CNR- Institute of Geosciences and Earth Resources – Turin Unit, Via Valperga Caluso, 35 – 10024 Torino (Italy); s.tallone@csg.to.cnr.it

This paper describes the architecture, kinematics and the effects on the structural setting of the Viù Deformation Zone (VDZ), a brittle transpressional tectonic feature affecting the northwestern border of the Lanzo Ultramafic Complex (italian Western Alps). The VDZ is constituted by N-S reverse-dextral faults linked by minor NW-SE sinistral-reverse faults, consistent with a roughly E-W shortening. Its dextral component is attested by the clockwise rotation of the syn-metamorphic features along this structure. Fault rocks indicate that the activity of the VDZ protracted from brittle-ductile to brittle conditions. Its activity caused the exhumation of the oceanic units, in the hanging-wall, with respect to the Lanzo Ultramafic Complex, in the footwall. Its geometry and kinematics indicate that it can be interpreted as a contractional step-over zone along the Col del Lis-Trana Deformation Zone, a N-S regional dextral-transcurrent brittle structure affecting the western border of the Lanzo Ultramafic Complex. These structures could be related to the transpressional event that affected in the Late(?) Oligocene-Early Miocene the inner sector of the Western Alps. This study also shows that the last phases of the Alpine tectonic evolution, largely neglected by the previous studies, strongly modified the syn-metamorphic structural setting of the innermost Western Alps.

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Exhumation, cooling and deformation history in the Adriatic rifted margin necking zone: the Campo/Grosina section (S-Switzerland and N-Italy)

Benoît Petri[1], Geoffroy Mohn[2], Jan R. Wijbrans[3], Gianreto Manatschal[1], Marco Beltrando[4]

1 EOST/IPGS CNRS UMR7516 r. Blessig, 67084, Strasbourg Cedex, France. Contact: bpetri@unistra.fr
2 Département Géosciences et Environnement, Univ de Cergy-Pontoise
3 Vrije Universiteit, Department of Geology and Geochemistry, de Boelelaan 1085, 1081HV Amsterdam, The Netherlands
4 Dipartimento di Scienze della Terra, Università di Torino, Italy

The Austroalpine units in SE Switzerland and N-Italy preserve the remnants of the Adriatic rifted margin.

Notably the Campo-Grosina units sampled the Adriatic necking zone where major crustal thinning was accommodated during the Jurassic rifting. This contribution aims to unravel the complex tectonic evolution recorded in these units from the late Carboniferous – early Permian to the Jurassic rifting. The cooling and exhumation of the Campo unit and the overlying Grosina unit, separated by the Eita shear zone are explored by the acquisition of 40Ar/39Ar on hornblende, muscovite and biotite. New geochronological data on the Grosina unit present 40Ar/39Ar ages between 273 and 261 Ma for muscovite and between 248 and 246 Ma for biotite. The Campo unit shows clearly younger ages between 210 and 177 Ma on hornblende, between 186 and 176 Ma on muscovite and between 174 and 171 Ma on biotite. Numerous data were discarded due to frequent excess 40Ar on amphiboles, probably associated to the emplacement of the Sondalo gabbro with a high 40Ar/36Ar ratio in Permian times. These new ages, together with a compilation of existing ages obtained with different chronometers (U–Pb, Sm–Nd, Rb–Sr, K–Ar, 40Ar/39Ar) and performed on different lithologies from both the Campo and the Grosina units allow to estimate cooling rates for these units. The new results show that both the Campo and the Grosina units underwent a cooling rate around 10°C/Ma in Permian time. The Grosina unit, being in a shallower crustal level, did not record the Jurassic cooling, reaching up to 50°C/Ma in the Campo unit. The notable difference in cooling rates between the Permian and the Jurassic events attests of a cooling without being associated to an exhumation in Permian times, whereas the Campo unit cooled rapidly in Jurassic times, associated to an exhumation and an emplacement in shallow crustal levels. The latter tectonic event was probably associates to shearing along the Eita shear zone and other greenschist facies shear zones located at the base and in the Grosina unit. These results bring new constrains on the strain evolution and the thermal budget of mid crustal levels during late orogenic extension and subsequent rifting.

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Permian magmatism, metamorphism and extension: implications for the Alpine Tethys rifting

Benoît Petri[1], Geoffroy Mohn[2]

1 EOST/IPGS CNRS UMR7516 r. Blessig, 67084, Strasbourg Cedex, France. Contact: bpetri@unistra.fr
2 Dépt. Géosciences et Environnement, Université de Cergy-Pontoise Contact: bpetri@unistra.fr

An orogenic cycle is likely ended by an important magmatic and metamorphic event in an overall extensional to transtensional tectonic context. In this post-orogenic context, the continental lithosphere will be strongly modified leading eventually to the formation of a "new" equilibrated continental crust, with a typical structural, lithological and thermal framework. This contribution aims to unravel the role of late- to post-orogenic inheritance for the development of subsequent rift events. In W-Europe, such an evolution was recorded during the Permian post-Variscan event. Fortunately, all levels of this "new" lithosphere were exhumed by Mesozoic rifting and Cretaceous to Tertiary compressive tectonics and are now outcropping in the Alps. From the base to the top, the pre-rift lithosphere preserved in the Alpine realm documents (1) Permian high partial melting of the subcontinental mantle associated with (2) emplacement of mafic magmas essentially at the base of the crust but also occasionally in mid- to upper crustal levels. Conversely, more acid magmas were likely emplaced in the shallower crustal levels. Together with a shallow lithosphere-asthenosphere boundary, the heat brought by these intrusions is responsible for (3) the regional high-temperature conditions and associated metamorphism. Finally, (4) numerous extensional structures and intra-continental basins are generated by the extensional tectonics within the former orogenic domain. By their potential control on the composition and the structure of the continental crust, post-orogenic modifications of the continental lithosphere may play a major role for the subsequent rift development, especially on localization/delocalization of the deformation and magmatic budget. This study has also implications for the tectonic, magmatic and metamorphic evolution of W-Europe during the Permian.

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High-temperature deformation in the gabbros from the Chenaillet ophiolite (Western Alps)

Pezzali I.[1], Manatschal G.[2], Sauter D.[2], Tribuzio R.[1,3], Zanetti A.[3]

1 - Dipartimento di Scienze della Terra e dell'Ambiente - Università degli Studi di Pavia (Italy) – irene.pezzali01@ateneopv.it
2 - EOST - Université de Strasbourg (France)
3 - C.N.R. - Istituto di Geoscienze e Georisorse, U.O. S. di Pavia

The Jurassic Chenaillet ophiolite (Western Alps) was only weakly affected by the Alpine tectono-metamorphic evolution and therefore preserves most of its pre-orogenic characteristics (e.g., Mevel et al., 1978; Bertrand et al., 1987). This ophiolite essentially consists of a gabbro-mantle association exhumed to the seafloor through detachment faulting, which is associated with a cover made up of basalt lavas (~400 m thick) and minor sediments (Manatschal et al., 2011). The gabbroic bodies mostly consist of undeformed troctolites including minor clinopyroxene-rich gabbros with widespread anastomosing ductile shear zones. The host mantle sequences are composed of spinel-plagioclase peridotites locally including spinel-plagioclase websterite layers. Preliminary petrological and geochemical data indicate: (i) depleted geochemical signature for the spinel facies mantle peridotites, and (ii) spinel facies websterite

veining by MORB-type melts associated with local refertilization of the peridotites.
Sheared gabbros show protomylonite to mylonite and ultramylonite structures and are locally associated with a network of felsic dykes. The latter commonly crosscut the shearing foliation at a high angle, but are in places involved into the ductile shearing event. The sheared gabbros commonly preserve igneous clinopyroxene porphyroclasts, whereas primary plagioclase is mostly recrystallized into poligonal aggregates. Neoblastic plagioclase has anorthite proportion ranging from 38 to 30 mol%. With respect to undeformed gabbros, the sheared gabbros are modally distinct in an increase of amphibole modal contents (up to 40 vol%). Amphibole (titanian edenite) occurs as corona around the porphyroclastic clinopyroxene or as sin-kinematic phase, locally associated with neoblastic clinopyroxene. The felsic dykes essentially consist of albite-rich plagioclase (An = 15-12 mol%) and minor titanian edenite (~10 vol%). Amphibole-plagioclase geothermometry documents that both the ductile shearing event and the crystallization of the felsic dykes occurred at 740-680 °C.
The undeformed and the sheared gabbros from the Chenaillet ophiolite have similar major element compositions. Conversely, incompatible trace compositions of the two rock-types are markedly different. The undeformed gabbros display a typical MOR-type geochemical signature (see also Costa and Caby, 2001), whereas the sheared gabbros show relatively high concentrations of incompatible trace elements. In the sheared gabbros, the increasing concentrations of incompatible elements are positively correlated with amphibole modal amounts, thereby indicating that the ductile deformation was associated with metasomatism. The felsic dykes are characterized by low Mg# [MgO/(MgO+FeOtot)] and high concentrations of incompatible trace elements.
The ductile shearing event affecting the Chenaillet gabbro was most likely associated with the exhumation of the gabbroic sequence at the ductile-brittle transition. We propose that the gabbro shearing was assisted by the amphibole-saturated melts feeding the felsic dykes. Because amphibole from both the sheared gabbros and the felsic dykes have low Cl concentrations (≤0.03 wt%), the amphibole-saturated melts are inferred to retain a negligible seawater component. Taken as a whole, the preliminary data argue against the idea of Caby (1995) that infiltration of seawater-derived fluids along ductile shear zones triggered partial melting of the gabbros. Trace element micro-analyses of minerals are presently in progress to substantiate our hypothesis and to unravel the genesis of the SiO2-rich amphibole-saturated melts.

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Asbestiform and non asbestiform environmental tremolite - actinolite in French Alps

Christian Picard

Chrono-environment 25000 Besançon / ISTerre – 38000 Grenoble

Asbestos ("amiante" in French) is the commercial term which designs six fibrous silicates (Chemical Abstract Service or CAS classification) : chrysotile in serpentine group ; asbestiform tremolite, asbestiform actinolite, asbestiform anthophillite, amosite and crocidolite in amphibole groups. BRGM has established maps showing the asbestos distribution in France (Dessandier & Spencer, 2005; Lahondère et al., 2001, 2012), particularly in the french Alps (Lahondère et al., 2012, 2013). These authors classified the "asbestos alea" on 5 levels where 0 represent free asbestos areas, and 4 represents zones where environmental asbestos is confirmed. In this last group, 9 asbestos occurrences are mentioned in the alpine Corsica, whose the Canari Mine (closed since 1965); and 7 occurrences in the western Alps (Termignon, Lanslebourg, Bessans and Val de Peas). At these zones we have to add the Chamrousse ophiolitic area where tremolite and actinolite fibers are associated with the serpentinized peridotites (Lahondere et al., 2013).
In these different areas Chrysotile is the most common asbestiform mineral. It is commonly associated to serpentinized peridotites, for instance in ophiolitic complexes. Constituted by long and flexible fibers, it is easily recognizable using MEB coupled to EDS. Tremolite and actinolite fibers which are often associated with chrysotile, or sometimes without chrysotile, ask more attention because these minerals could be asbestiform or non asbestiform depending of their morphology and some specific crystallographic properties. Asbestiform tremolite and actinolite must have high L/D properties (L/D > 20), diameters bellow 3 µm and length bellow 25µm. They also need to be not the product of cleavage fragments, and instead be the product of crystal growth during hydrothermal processes. As for chrysotile, their characterization required MEB coupled to EDS, but also MET for observation of diffraction figures which seem different for asbestiform and non asbestiform tremolite and actinolite. All these investigations are presently under progress.

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Preliminary results of K-Ar dating of clay fault gouges from the SAva and Idrija faults (Slovenia) and the Ribnovo fault (Bulgaria)

Pleuger, Jan[1,2], Zwingmann, Horst[3], Skaberne, Dragomir[4], Vrabec, Marko[5], Georgiev, Neven[6] and Mancktelow, Neil[2]

1 Institut für Geologische, Freie Univ. Berlin, Malteserstraße 74-100, 12249 Berlin, Germany, jan.pleuger@fu-berlin.de
2 Geologisches Institut, ETH Zürich, 8092 Zürich, Switzerland
3 CSIRO Earth Science and Resource Eng., Bentley WA 6151, Australia
4 Geol. Survey of Slovenia, Dimičeva ulica 14, 1000 Ljubljana, Slovenia
5 Dept. of Geol Univ. of Ljubljana, Aškerčeva cesta 12, 1000 Ljubljana, Slovenia
6 Dept. of Geology, Palaeontology and Fossil fuels, Sofia University St. Kliment Ohridski, 15 Tzar Osvoboditel Blvd., 1504 Sofia, Bulgaria

In many cases, the age of movements along brittle faults can be constrained by low-temperature geochronological methods (like fission track dating) or the interplay between faulting and magmatic activity and/or sedimentation in syntectonic basins. However, these approaches will fail where the vertical offset along a fault is small, such as for strike-slip faults, or where magmatic and sedimentary time markers are lacking. In such cases, K-Ar (or encapsulated 40Ar/39Ar) dating of clay fault gouges is a potential method for dating the activity of brittle faults. Previous studies yielded plausible results especially in crystalline basement terrains where all clay contained in the gouge is expected to be authigenic and, ideally, newly grown illite is the only potassium-bearing mineral phase in the gouge. In such a case, illite may grow at different times during protracted faulting and ages obtained from K-Ar dating would reflect only an instant of a longer faulting period. Whether this instant is closer to the onset or the end of faulting depends on various factors such as contamination of the gouge by protolith material and the growth kinetics of illite (or other K-bearing minerals) during faulting. Ample presence of protolith material may bias the data towards ages predating fault activity. On the other hand, illite growth may continue after fault activity has ceased. In order to assess these factors, we sampled gouges in Slovenia and Bulgaria where brittle faults of (apparently) well-constrained age developed in completely different country rocks that are significantly older than faulting. K-Ar dating was performed on the <2µm fraction separated from the fault gouges. The Ribnovo fault in southwest Bulgaria affects gneisses, schists, and marbles of at least Late Jurassic age that do not contain clay minerals. A gouge sample from this fault gave an age of 35.1±0.7 Ma, which coincides exactly with the time of faulting as constrained by syntectonic sediments and crosscutting relationships with igneous rocks. For the Idrija and Sava faults in northwest Slovenia, a post-Sarmatian (post-12 Ma) activity is documented by their relationships with the South Alpine thrust front and pre-tectonic sediments, respectively. For the Sava fault, the samples yielded ages of 87.8±1.8 Ma and 44.6±0.9 Ma. The protoliths are Middle to Upper Triassic marly schists and Middle Triassic shales and carbonates, respectively. The samples from the Idrija fault were collected from a trench made by the Geological Survey of Slovenia in 2012. The protoliths of the gouges are Upper Permian dolostone and sandstone of the Gröden formation. From individual branches of the Idrija fault, we obtained three fault gouge ages of 108.1±2.2 Ma, 111.1±2.2 Ma, and 113.1±2.3 Ma. Clay separated from the Gröden sandstone protolith yielded an age of 82.3±1.7 Ma. The data from the Sava and Idrija faults are obviously older than the commonly assumed timing of these faults. Although further investigations (mineralogical characterisation of the gouge, dating of finer-grained fractions) may help to solve this dilemma, we draw the following preliminary conclusions. (1) Ages from the Idrija fault do not reflect the time of faulting but Cretaceous growth of illite, probably promoted by fluids circulating in the highly porous Gröden sandstone. (2) Irrespective of the true age of faulting, the fact that fault gouge ages from the Idrija fault are older than ages for the clay size fraction of the protolith can be explained by reduced illite growth (fluid activity) within the gouge once it is formed. (3) Radiometric fault gouge dating is more likely to give plausible and more easily interpretable results if the protolith is free of precursor clay.

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The Deep Alps and the Eastern Alpine Seismic Investigation (EASI) project

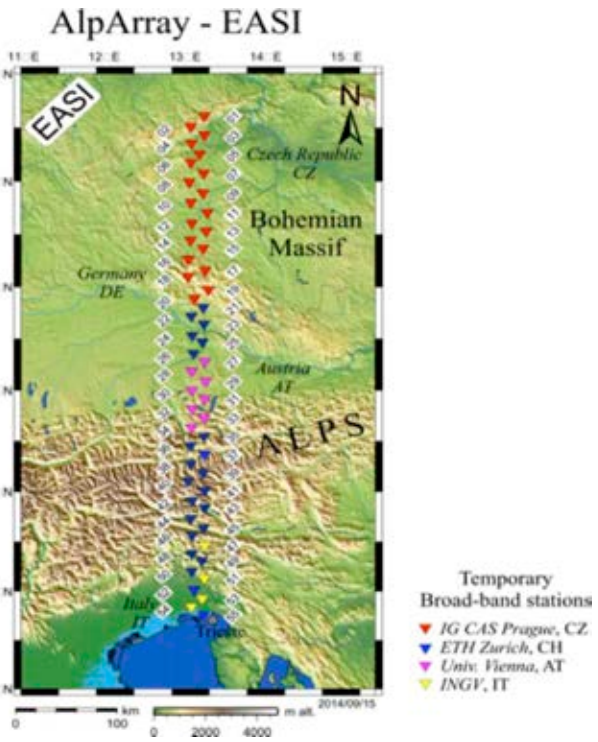
Plomerová, J., Bianchi, I., Hetényi, G., Munzarová, H., Bokelmann, G., Kissling, E. AlpArray-EASI Working Group and AlpArray-EASI Field Team

Inst. of Geophysics, CAS, Bocni II, 141 31 Prague 4, Czech Republic

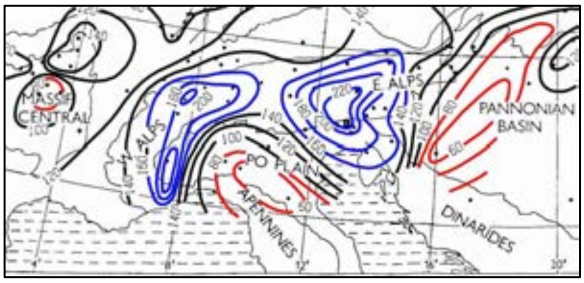
AlpArray(http://www.seismo.ethz.ch/research/groups/alrt/projects/alparray/) is a large European initiative to study the entire Alpine orogen at high resolution and in 3D with a large variety of methods. The core element of the initiative is an extensive and dense broadband seismological network. In addition, a number of Complementary Experiments will be conducted to focus on targeted problems.

The first implemented AlpArray Complementary Experiment is called Eastern Alpine Seismic Investigation (EASI). The Eastern, “straight“ part of the Alps is home to a number of open questions, e.g., the origin of the hanging lithospheric slab (Adriatic or European?), the nature of the Moho “hole” between the two plates, the anisotropic nature of the lower crust, and the relationship of the Alpine orogen to the adjacent foreland basin and the lithospheric blocks of the Bohemian Massif. Our research methods include tomography, ambient noise analysis and receiver functions, with anisotropy included in all three types of investigations as well as in shear-wave splitting analyses. The depth range of investigations encompasses the crust and the mantle lithosphere, down to the LAB.

In this presentation we detail the design of the experiment. EASI is composed of 55 broadband seismic stations, deployed in a zig-zag pattern on either side of the central longitude line of 13.35°E. The planned north-south distance between stations was 10 km, the distance of each station to either side of the central line was 6 km. We aimed to keep the stations within 1.5 km of the target location, as much as topographic, field and infrastructure condition allowed.



The result: with respect to the original deployment plans the closest match is 164m, 10 stations are within 500m, 31 stations are within 1.5km which is also the average match, and the farthest is 4.4km. The overall result remained a very linear and regularly spaced array, spanning 540 km from the Czech-German border to the Adriatic Sea. The highest elevation station is at 1846m, the lowest at sea-level (average: 646m). The achieved geometry leads to a uniform ray coverage at depth considering that the majority of the teleseismic events are coming from North and East directions (e.g. Japan, and Pacific Ocean) and few are arriving from South and West directions (Africa and Atlantic Ocean).
The pool of 55 seismic stations is gathered from the research institutions of ETH Zürich (23), IG-CAS Prague (20), the Geophysics Department of the University of Vienna (8) and INGV (4). A few stations are equipped with telemetry and several stations report daily state-of-health sms messages. The construction and maintenance of this profile constitutes a deployment of a narrow extent, but a big collaborative effort.



Separated lithosphere roots of the W. and E. Alps (Babuška etal., Tectonophys. 1990, Babuška and Plomerová, 1992).

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From Drina-Ivanjica Paleozoic to Western Vardar Ophiolite: from nappe-stacking to post-emplacement deformations in Western Serbia – preliminary results

Kristóf Porkoláb[1], Szilvia Kövér[1], Balázs Soós[1], Nataša Gerzina[2], Nevenka Đerić[2], László Fodor[1]

1- 1117 Budapest, Pázmány s.1/c, MTA-ELTE Geological, Geophysical and Space Science Research Group, kristof.porkolab@gmail.com
2- Faculty of Mining and Geology, University of Belgrade

In the Zlatibor area (western Serbia) Middle Jurassic ophiolitic and continent-derived (Drina-Ivanjica) tectonic units crop out. The Paleozoic and Mesozoic succession of the Drina-Ivanjica thrust sheet forms a tectonic window below the ophiolitic nappe (Schmid et al., 2008).
However, in the Tara National Park (westernmost Serbia), thin tectonic slices of Middle Triassic to Early Jurassic non-metamorphic carbonate succession occurs in a topographically higher position than the mélange and the ophiolite. According to the first field measurements, the structural position of these continental slices could be explained by Paleogene to Miocene out-of-sequence thrusting, thus juxtaposing the lower, continental unit and the primary upper, oceanic one. In this case, an important question is the methamorphic history of the continental Drina-Ivajica slice, being the possible origin of the carbonate slices.
According to field observations, the Paleozoic sequence of the Drina-Ivanjica was subjected to several folding phases and ductile deformation connected to metamorphism up to greenschist facies. The age of the metamorphism is uncertain, though few data suggest Alpine metamorphism. One aim of this project is to provide age data for the metamorphic overprint. However, the overlying Mesozoic sequence, which was attributed to the Drina-Ivanjica Unit, does not show tight folding, ductile deformation or metamorphic overprint. If the Alpine age (ca. 120 Ma) of metamorphism will be confirmed, then the relationship of Palaeozoic and Mesozoic successions should be revised; the Mesozoic would represent a different tectonic unit.
The post-Late Cretaceous deformation history of the study area is complex. Strike slip movements and the mentioned out-of-sequence thrusting might have occured

in the Paleogene due to N-S to NE-SW compression. In the Miocene, back-arc extension took place, resulting in formation of small basins and moderate redistribution of the Jurassic, Cretaceous, and Paleogene nappe order due to normal faulting. In order to reveal the whole tectonomethamorphic evolution, we plan to apply illite crystallinity, Raman-spectroscopy, thermochronological methods, and detailed structural analysis.

The research project is supported by Hungarian National Fund OTKA 113013 and the Bilateral Serbian-Hungarian Academic Exchange Project.

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Western Alps Tomography and Moho Topography Determination using 35,000 Local Earthquakes

Potin Bertrand[1], Valette Bernard[2], Thouvenot François[1], Monteiller Vadim[3]

(1) ISTerre – Université Grenoble-Alpes – CNRS, Grenoble, France (bertrand.potin@ujf-grenoble.fr)
(2) ISTerre – IRD – Université Savoie-Mont-Blanc, Chambéry, France
(3) Geoazur, Nice-Sophia-Antipolis, France

Over the past 25 years, several dense seismic networks settled in France, Italy and Switzerland have permitted to locate more than 35,000 local earthquakes. Using 345 stations spread over a 425x450 km square area, and more than 800,000 data, we performed a tomography in order to determine P-wave velocity, vP/vS ratio as well as earthquake location.
Our crust and upper mantle tomography is based on travel-times analysis. The model consists of a set of VP and VP /VS values given at each node of a three-dimensional, regularly spaced grid, which constitutes the inversion grid. Transition between crust and mantle is modeled by a continuous change in velocity, as we do not introduce any a priori information on the Moho interface. Earthquake locations and site-effect residuals at each station are also determined in the process. The forward computation of travel times in the 3D model is performed by integrating slowness along the rays, which are determined by the Podvin-Lecomte algorithm (basically a finite difference resolution of eikonal equation). Inversion is carried out using a non-linear least-squares approach based on a stochastic description of data and model. The smoothing and damping parameters are adjusted by means of L–curves analysis.
The Moho discontinuity is obtained by an iso-velocity surface of this tomography model, in accordance with information coming from several other regional studies. This new Moho interface is then used as an a priori discontinuity in a new tomography process in which the parameters within the crust and the upper mantle are now decorrelated. Thus, refracted waves are modeled more correctly and the resolution within the crust can be improved.

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Present-day deformations of the Jura arc inferred by GPS surveying and earthquake focal mechanisms

Rabin Mickael[1], Sue Christian[1], Sakic Pierre[2], Walpersdorf Andréa[3]

1: Université de Franche-Comté, Besançon. mickael.rabin@univ-fcomte.fr ; christian.sue@univ-fcomte.fr
2 : Université de La Rochelle. pierre.sakic@univ-lr.fr
3 : ISTerre, Grenoble. andrea.walpersdorf@ujf-grenoble.fr

The Jura Mountain is the most recent expression of the alpine orogeny. Located at the northern end of the western Alps, the Jura is one the best studied orogenic arc in the world but its recent deformation is still a matter of debates. GPS data available in the Jura Mountains bear witness of disagreement between the different studies (Jouanne et al., 1998; Schlatter et al., 2005; Walpersdorf et al., 2006), their interpretations vary from uplifted belt (Jouanne et al., 1998) to arc-parallel extension and very slow horizontal movements (Walpersdorf et al., 2006). Moreover, the traditionally accepted model of an active collisional activity of the Jura, in the dynamic continuity of the Alps, rises up the matter of its geodynamic origin. The European Alps are in a post-collisional regime (Champagnac et al., 2009; Sue et al., 2007; Nocquet, 2012), and are characterized by isostatic-related extension and uplift, due to the interaction between buoyancy forces and erosional dynamics (Champagnac et al., 2007; Vernant et al., 2013; Serpelloni et al., 2013).
In order to characterize the neotectonic activity of the Jura arc, we present a reappraisal of published focal mechanisms combined with a new GPS solution over the entire arc and surrounding areas. Although the Jura presents a low seismic activity, 53 focal mechanisms over the Jura realm have been inverted in order to infer the current stress field around the belt. Anyhow, we tested several combinations of f.m. inversions, by structural zones, in order to test the regional stress stability.
We compare our inversions with the global inversion performed by Kastrup et al. (2004) for the global dataset. It appears that the current stress field is very stable all over the arc, and following our different sub-datasets. Indeed, the stress field shows a stable near horizontal NW-SE-oriented s1, associated to a NE-SW-oriented s3. Therefore, the structural arc of the Jura seems to have no impact in terms of current stress.
In a second time, we present preliminary velocity and strain fields from a GPS network composed of 25 permanent stations implemented between 1998 and 2014 all around the Jura arc. Indeed, we also integrated the GPS-JURA station, but they are still too young to accurately constrain the strain of the belt. Preliminary

results (Sue et al., 2014) exhibit very slow velocities across the arc in term of baselines evolution, with infra-millimetric yearly velocity (0.1 to 0.3 mm/yr). They are compatible with low compression perpendicular to the arc, associated to low extension parallel to the arc. In terms of vertical motions, we obtain low positives velocity, compatible with the results of Serpelloni et al. (2013) at the scale of the Alps.

This work remains to be strengthened by further analysis. Anyhow, the Jura arc seems currently undergoing an overall transcurrent tectonism, both in terms of stress and strain field, with a (very) low uplift. This tectonics frame could be responsible for the reactivation of transcurrent faults such as the Vuache fault (Thouvenot et al., 1998).

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Neotectonics of a slow orogenic arc inferred from quantitative geomorphology: the Jura Mountains.

Rabin M.[1], Sue C. [1], Champagnac J.-D.[2], Valla P.G. [3], Carry N. [1], Eichenberger U[4], Bichet V. [1], & Mudry J. [1]*

1 Chrono-environnement, UMR 6249. University of Franche-Comté, 16 route de Gray 25000 Besançon. France (mickael.rabin@univ-fcomte.fr)
2 Geologisches Institut. ETH-Zürich 8092 Zürich. Switzerland
**now at Leysin*
3 Institute of Earth Surface dynamics. University of Lausanne
4 ISSKA, 68 rue de la Serre CH-2301 La Chaux-de-Fonds.

The Jura has been well studied from a structural point of view, but still remains the source of debates, especially regarding its current and recent tectonic activity. It is deemed to be always in a shortening state according to geomorphologic and stress/strain data, but geodetic studies available on the Jura involve disagreement between authors.

The study of the neotectonic activity in the Jura Mountain (northwestern most belt of the European Alps) represents a challenge in the application of quantitative geomorphology to extract landscape metrics and discuss the coupling between tectonic, climatic and lithospheric mechanisms in mountain belt evolution. The Jura Mountains are characterized by a karstic calcareous bedrock, slightly affected by Quaternary glaciations, and by moderated uplift rates (< 1 mm/yr). In this study, we performed river profile analyses to draw a map of comparable geomorphological signals along tectonic structures within the entire Jura arc. Our results highlight higher tectonic activity in the High Range (internal part) than in the External Range, which is discussed in terms of deformation mechanisms.

By comparing our results with geomorphological, neotectonic and geodetic studies, we propose new hypotheses to explain the potential mechanism(s) driving the Plio-Quaternary deformations of the Jura Mountains. Our study reveals a regional-scale correlation between neotectonic deformations recorded by the Jura drainage network and the predicted isostatic rebound in response to Alpine Quaternary erosion. However the coexistence of an ongoing horizontal shortening in the External Range at least until early Pleistocene times may have also impacted the Jura river profiles.

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Reconstructing the sediment provenance of the Voirons Flysch (Gurnigel Nappe, Haute-Savoie, France)

Ragusa Jérémy, Kindler Pascal and Segvic Branimir

University of Geneva, Section des Sciences de la Terre et de l'environnement, CH-1205 Genève, Switzerland (jeremy.ragusa@unige.ch)

Recent provenance analyses for the Voirons Flysch suggest a generic feeding model for the Gurnigel nappe which involves the Sesia-Dent Blanche nappes, the sedimentary nappes incorporated in the Prealpine accretionary prism, and probably the Briançonnais basement.

The Chablais Prealps (Haute-Savoie, France) represent a well-preserved accretionary wedge in the Western Alps. It comprises a stack of décollement nappes thrusted in a northward direction and originating from diverse paleogeographic domains from the Ultrahelvetic realm (distal part of Dauphinois domain) to the southern part of the Piemont Ocean. The present study focuses on the Gurnigel Nappe that is well represented in the Voirons Massif. There, it is subdivided into four turbiditic formations (from bottom to top):

the Voirons Sandstone Fm. (VS) representing distal channel to lobe deposits, the Vouan Conglomerate Fm. (VC) composed of proximal channel deposits, the Saxel Marls (SM) Fm. represented by distal lobe deposits, and the Bruant Sandstones Fm. (BS) which are similar to the VS.

Recent biostratigraphic results (planktonic foraminfers) yielded a Middle to Late Eocene age for the Voirons Flysch, which was long believed to range from the Paleocene to the Middle Eocene (based on calcareous nannofossils). This younger age is in disagreement with most palaeogeographic models, which propose a south-Penninic origin for this flysch, and correlate it with the Upper Prealpine nappes.

A paleogeographic origin in the Valais domain is more compatible with this young age. Because provenance interpretation is largely based on results from the other flysch deposits of the Gurnigel nappe, the aim of the

present study is to determine the sediment provenance for the Voirons Flysch to help resolve this palaeogeographic conundrum.
A total of 270 thin sections collected from the four members of the Voirons Flysch were prepared, from which we subsequently stained the feldspars and counted circa 300 grains following the Gazzi-Dickinson method. Nineteen samples were used for extracting heavy-mineral assemblages. QemScan analyses were further made to get a first semi-quantitative heavy mineral analysis.
Our results show that, in contrast to the other flyschs from the Gurnigel nappe, the Voirons Flysch was fed by two major sources, hereafter called the Voirons and the Vouan provenance. The Voirons provenance is the most important one. It supplied three of the four studied formations, and is similar to the source of the other flysch deposits from the Gurnigel Nappe. It is characterized by a quartzose assemblage with sedimentary to granitic lithoclasts, and a heavy-mineral population dominated by the ZTR mineral group. According to the Garzanti model, these observations suggest a Continental Block to Clastic Wedge provenance as the dominant source for the VS, SM, and BS. The Vouan provenance characterizes the VC and is derived from a feldspathic source associated with metamorphic clasts, and a heavy-mineral population characterized by garnet. According the Garzanti model, this provenance is related to basement unroofing in the Axial Belt domain.
We propose a generic model of sedimentary inputs for these two provenances. The more mature composition of the Voirons provenance is related to the reworking of units already included in the accretionary prism (Upper Prealpine nappes and Klippen nappe). Crystalline rock fragments were provided by the partially subducted Sesia-Dent Blanche nappes. The latter is the main source of the Vouan provenance, providing metamorphic rock fragments mostly derived from the Arolla and Valpelline units.

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Discontinuities in structural and metamorphic history across a nappe stack: mapping the location and geometry of the Combin Fault (Western Alps)

Real Christophe[a], Manzotti Paola[a], Le Goff Elisabeth[b], Dal Piaz Giorgio V[c], Ballèvre Michel[a]

a Géosciences Rennes, UMR 6118CNRS, Université Rennes1, 35042 Rennes, France, real.christophe@univ-rennes1.fr
b BRGM – Service des Actions Régionales, 1049 rue de Pinville, 34000 Montpellier, France, e.legoff@brgm.fr
c Dipartimento di Geosienze, Università degli Studi di Padova, via G. Gradenigo 6, 35131 Padova, Italia

In the Western Alps, oceanic units are sandwiched in between continental units derived from both palaeomargins A major discontinuity has been recognized within the oceanic units (e.g. Dal Piaz, 1999), separating eclogite-bearing units at the base (the Zermatt zone) from dominantly greenschist-facies units (with blueschist relics) at the top (the Combin zone). However, due to the strong greenschist-facies overprint in the higher units, no consensus has been achieved on the exact location and geometry of the Combin Fault, and its relationships with the underlying Zermatt zone.
Detailed mapping has been made in a classic area (the Cignana area, in the upper Valtournenche, Italy) in order to solve this geometrical problem. From base to top, one can recognize (i) eclogite-bearing ophiolitic units, displaying well-preserved HP and UHP rocks (the classic Zermatt Zone); (ii) metabasalts (rarely preserving garnet and glaucophane, and strongly overprinted at albite-epidote amphibolite facies) and calcschists, (iii) a slice of serpentinites preserving on top their sedimentary cover (ophicalcites, micaschists and manganiferous cherts), (iv) a thin sheet of Permo-Mesozoic sequences, detached from their pre-Alpine basement (the Cime Bianche Unit), and (v) calcschists displaying a few lenses of metagabbros (Tsaté nappe).
Some authors place the Combin Fault at the base of the Cime Bianche Unit (e.g. Pleuger et al., 2007; Groppo et al., 2009; Kirst, 2014; Steck et al., 2015), while others prefer a solution where the Combin Fault is located deeper in the nappe stack, within the ophiolitic sequences (e.g. Ballèvre and Merle, 1993; Dal Piaz, 1999; Bucher et al., 2003; Compagnoni and Rolfo, 2003; Negro et al., 2013; Dal Piaz et al., 2015). In accordance with this latter hypothesis, petrological and structural criteria will be used to show that the main discontinuity in the nappe stack (i.e. the Combin Fault) occurs at the contact between units (i) and (ii), and that this contact intersects large-scale folding reworking previous eclogite-facies shear zones within the underlying Zermatt zone.
This geometry has major consequences (i) for the geometry of the large-scale folding of the nappe stack during the later stages of the Alpine history (especially the Mischabel backfold), (ii) the meaning of the (refolded) shear criteria used to decipher the kinematics of emplacement of the different units, and (iii) for the rheology of the serpentinites during subduction.

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Continental tectonics related to subduction dynamics during India-Asia convergence

Replumaz, Anne

Université Grenoble Alpes, CNRS, ISTerre, F-38000 Grenoble, France, anne.replumaz@ujf-grenoble.fr

Continental tectonics during collision must ultimately relate to the subduction zones dynamics, where the fundamental tectonic forces originate. However, the observed complex patterns and evolution of continental tectonics are not easily reconciled with the reconstructed subduction histories, so that the relation between margin and continent interiors processes remains largely unconstrained.
The long term evolution of Indian lithosphere during the indentation process has been deduced from remnants of slabs in the mantle shown by P-waves global tomography (Replumaz et al., 2010). A complete breakoff occurs at the transition between the Tethys oceanic subduction and the Indian continental one (OCB), then the Indian lithosphere resumes subducting (figure 1). Comparing global tomographic images and Asian tectonics reconstruction, allows formulating hypotheses on how deep subduction and indentation tectonics are coupled, tested by doing analogue and numerical models.
Analogue modelling using silicone as analogue of lithosphere and glucose syrup as analogue of mantle, show that a lighter continental lithosphere attached to a denser oceanic lithosphere is dragged into the mantle, but with a strong horizontal component of motion, generating the indentation of the upper plate (Bajolet et al., 2013). Such indentation could even drive the subduction of continent in the upper plate, with opposite dip as the indenter, as observed present-day in the Pamir (Negredo et al., 2007), or in Central Tibet (Guillot and Replumaz, 2013).
More complex numerical models of coupled subducting/upper plates in an ambient mantle, show that when the slab detaches at the OCB, the subduction of the buoyant continent resumes in the middle of the continent, not attached to the dense oceanic slab (figure 1). The breakoff affects the continuity of the slab but the vertical convective cell extends throughout the upper mantle, and the poloidal mantle flow in the slab center drives the subduction of the continent (Capitanio and Replumaz, 2013). After the breakoff, the slab vertical continuity is lost but stresses propagate to surface through the mantle viscous coupling. On the contrary, the toroidal flow at the slab edge is strongly affected by breakoff, so that the shallow lithospheric tip is not dragged into the mantle, resulting in the indentation of the upper plate. Slab deformation accommodates the different dips along the trench, and the trench curves progressively. Transient stresses resulting of such stress coupling gradients at the trench, propagate far into the upper plate interiors, localizing along a belt at a high angle with the trench, with a trend similar to the major lithospheric faults of Asia. The successive breakoff episodes evidenced using global tomography likely provided the conditions for episodic nucleation of lithospheric faults within the Asian continent and their link to deep processes.

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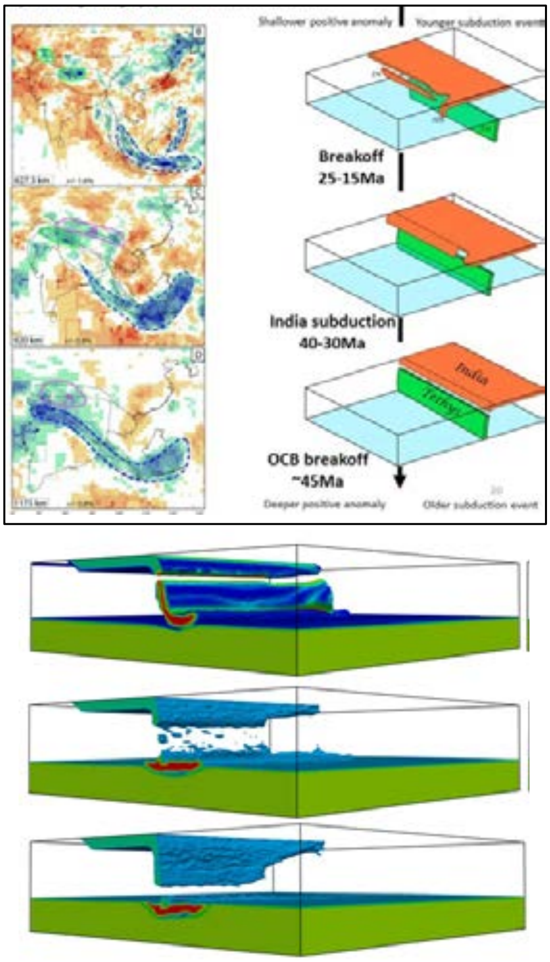

Figure 1: (up)/ evolution of the geometry of the global tomographic positive anomalies (in blue) with depth, related to subduction events during the India/Asia collision (Replumaz et al., 2010).
(down)/ 3D numerical model of complete slab breakoff at the OCB followed by the subduction of the buoyant continent (Capitanio and Replumaz, 2013).

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High incision rates evidences in the SW Alps following the Last deglaciation: Relative roles of climate and tectonics

Rolland Yann[1], Petit Carole[1], Saillard Marianne[1], Braucher Régis[2], Bourlès Didier[2], Darnault Romain[3], Cassol Davide[1].

1 Géoazur, UMR7329-CNRS, UNS, 250 rue Albert Einstein, Sophia Antipolis, 06560 Valbonne France.
2 Aix-Marseille Université, CNRS-IRD-Collège de France, UM 34 CEREGE Aix-en-Provence, France
3 IFP-Energies nouvelles, Rueil-Malmaison, France.

To study the relationship between denudation, climate and tectonics, polished river surfaces from the Tinée and Vésubie Rivers in the French 'Alpes Maritimes' region (SW Alps) were sampled to perform in situ-produced cosmogenic nuclide dating. The in situ-produced 36Cl and 10Be concentrations were measured for this purpose, respectively, within calcite and quartz samples collected at regular heights along 30-meter high transects.
The determined 36Cl and 10Be Cosmic-Ray Exposure (CRE) durations of the sampled river polished surface mainly range from 1-3 to 20 ka, i.e., overall after the Last Glacial Maximum. This implies that the studied rivers incised at rates ranging from 1 to 5 mm/a. More precisely, the incision rates exhibit two peaks reaching ~2 mm/a and 4–5 mm/a at 4–5 ka and 11–12 ka, respectively, separated by a period experiencing a lower incision rate (~1 mm/a), which is interpreted as resulting from recent climatic changes (Saillard et al., 2014). Furthermore, the local effect of post-glacial incision of gorges, corresponding to steps in the geomorphology at the foot of the high flat part of valleys and governed by cap-glacier dynamics during the LGM, leads to incision rates higher than 1 cm/a. These variations do not strongly affect the general shape of the river profile and suggest that the measured short-term incision rate is dominated by a climatic signal, which does not preclude the possible role of tectonic uplift.
It can thus be concluded that in the studied settings vertical profiles of rivers do witness the climatic fluctuations that resulted in variable precipitation rates, and thus in variable net water fluxes and denudation rates in the watershed. Meanwhile, the longitudinal river profiles do not still have reached equilibrium following the cumulated effect of glaciations that occurred in the last several 100th of ka. Variable along-stream incision rates may be ascribed to steps in the geomorphology inherited from the previous glacial cycles, while, based on the literature, an average 1mm/a contribution could be ascribed to tectonic uplift.

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Synthesis of ages obtained by direct dating of Alpine External Crystalline Massifs shear zones – Insights for an Oligocene-to-Present underthrusting-exhumation cycle

Rolland Yann[1], Bellahsen Nicolas[2], Boutoux Alexandre[2], Lanari Pierre[3], Cenki-Tok Benedicte[4], Dumont Thierry[5], Rossi Magali[6], Verlaguet Anne[2].

1 Géoazur, UMR7329-CNRS Sophia Antipolis, 06560 Valbonne France.
2 UPMC Univ Paris 06, CNRS, ISTeP, 4 place Jussieu 75005 Paris.
3 Dept. of Geological Sciences, University of Bern, , CH-3012 Bern.
4 Geosciences Montpellier, , University of Montpellier, France.
5 ISTerre, , University of Grenoble, France.
6 EDYTEM, UMR 5204, University Savoie-Mont-Blanc,France.

In order to constrain the burial-exhumation cycle of continental crust during the Alpine orogeny we have sampled several shear zones, which record specific stages the deformational history of the External Crystalline Massifs (ECM) that include the Aar-Mont Blanc-Pelvoux-Argentera massifs. We have performed high-resolution geochronology on a large number of shear zones and veins. Techniques used include single-grain 40Ar/39Ar dating (step heating), U-Th-Pb in situ dating of allanite by LA-ICP-MS and Rb-Sr geochronology. These ages are compared to U-Th-He ages on apatite/zircon in order to decipher the pressure-temperature-time evolution of deformed rocks making the ECM in general. From these examples, our major conclusions are: In cases of a single deformational stage, all techniques yield similar ages, which is ascribed to the crystallization of minerals during ductile deformation in a short time (<0.2 Ma, within error). In other cases of several ages recorded by the various chronometers, this is due to a multi-stage deformation history for which the minerals are more or less prone to reset. Thus, these techniques do provide crystallisation ages associated to a deformation/fluid circulation stage, and ARE NOT cooling ages.
Several stages of shear zones development are evidenced: (i) underthrusting of the ECM at 33-29 Ma, which is interpreted as the activation and activity of the Penninic front, and (ii) further close-to-pressure peak transpressional deformation between 30 and 20 Ma, (iii) strike-slip transpressional deformation in several stages during exhumation between 20 and 10 Ma in both the Mont Blanc and Aar massifs. Uplift is further recorded by U-Th-He ages on apatite, which could be ascribed to some 'cooling ages' below 70-100°C, mostly after 10 Ma. It appears not to be related with erosion induced by glacial-deglacial stages, but rather to a sequence of thrust activation at the front of the ECM. We can conclude that together with companion presentations (Lanari et al., Bellahsen et al.) punctual mineral dating pinpoint shear zone activity and can be used to decipher the burial-exhumation cysle in a mountain belt. The ECM underwent burial between 33 and 30 Ma, followed by

exhumation at ca. 16 Ma, which is well verified along the belt.

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Topography of the Central Alps in the light of collisional tectonics

Claudio Rosenberg, Marianne Janowski, Nicolas Loget, Sebastian Garcia

ISTeP, UPMC, 4 place Jussieu, Paris. claudio.rosenberg@upmc.fr

The distribution of collisional shortening, between upper and lower plates in the Central Alps, varies along strike (Rosenberg and Kissling, 2013). North of the Insubric Line, the amount of post-nappe shortening increases westwards, whereas south of the Insubric Line, post-nappe shortening increases eastward (Schönborn, 1992). Taking the Bergell pluton as a time marker, the age of these deformations is inferred to be post 30 Ma.

We investigate the present-day topography of the Central Alps, in order to test whether these along-strike changes, in the amounts of shortening are associated to a change in the topographic signature or geomorphic indexes. In order to do so, swath topographic profiles with mean, maximum and minimum elevations were analysed as well as local relief. These data show that local relief varies following two along-strike trends:

1. North of the Insubric Line, the relief decreases from west to east, showing the transition from a highly incised topography in the west to a plateau-like topography in the East.
2. South of the Insubric Line, the relief increases from East to West.

Existing estimates of Miocene exhumation rates north of the Insubric Line (Fox et al., 2015; Rosenberg et al., 2015, for compilation) point to a west-directed increase of ~ 0.5 orders of magnitude between the Campo/Ötztal-, to the Simplon area. These trends point to a correlation between amount of shortening, exhumation rate, and intensity of local relief. Interestingly, no such a correlation is observed with respect to the mean elevation on either side of the Insubric line. Linear correlations between local relief and uplift rate (e.g. Hurtez et al., 1999), and between local relief and shortening rates (Champagnac et al., 2012) have been inferred for different, tectonically active areas in case of steady state trends. Therefore, a still active, westward increase of shortening and uplift rates, north of the Insubric Line, and a similar eastward-directed increase south of the Insubric Line could be suggested. However, given the very slow, present-day, convergent movements across the Central Alps (Noquet and Calais, 2004) it is difficult to interpret the above described relief gradients in terms of active, along-strike gradients of shortening- and uplift rates. In order to understand the more recent part of topographic evolution we calculated steepness indexes of rivers, and used them as proxys for recent uplift rates (Kirby and Whipple, 2012). These show an eastward increase, south of the Insubric Line, but they do not increase westward, north of the Insubric Line. Hence, this morphometric index does not seem to be correlated with the inferred gradients of collisional shortening described above.

Based on the observations above, we conclude that the present-day relief of the Central Alps, irrespective of the mean elevation, still reflects shortening gradients that shaped the Alpine Chain mainly during Miocene time. However, the lack of a correlation between relief and steepness index probably indicates a rejuvenation of the topography that evolved from adapting to gradients of collisional shortening in the Miocene to a more global uplift in recent times.

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Fluid-assisted deformation and recrystallization related to CO2-rich hydrothermal fluids: the case of the Valdieri marbles (Maritime Alps)

Rossetti, P.[1], Barale, L.[1], Bertok, C.[1], d'Atri, A.[1], Gerdes A.[3], Martire, L.[1], Piana, F.[2], Scarrone F[1]

1 Dipartimento di Scienze della Terra, Università di Torino, Italy
2 CNR-IGG, Istituto Geoscienze e Georisorse, Torino, Italy
3 Goethe Universität Frankfurt am Main, Germany

In the Maritime Alps, at the NE border of the Argentera crystalline massif, some hectometre- to kilometre-scale rock bodies of marbles, quarried in the past as ornamental stones ("Marmi di Valdieri"), occur within a carbonate succession referable to the Dauphinois domain and consisting of dark marls (Entracque Marl, Middle Jurassic-Berriasian), micritic limestones with breccia beds (Lausa Limestone, Valanginian-early Aptian), dark shales and marls (Marne Nere, Aptian-Cenomanian) and marly limestones (Puriac Limestone, Turonian-Campanian). The Puriac Limestone is unconformably overlain by middle Eocene-lower Oligocene sediments of the Alpine foreland basin.

Recrystallization affects the Lausa Limestone, the Marne Nere, and the lower and middle portions of the Puriac Limestone. The marbles pass gradually to poorly recrystallized rocks in a range of few tens of meters.

The Valdieri marbles lower part (corresponding to the Lausa Limestone) consists of pure white and grey marbles with rare mm-thick elongated and folded domains

strongly enriched in muscovite, K-feldspar, albite and quartz. The upper part (corresponding to the Puriac Limestone) is composed of lens-shaped, cm- to dm-thick granoblastic marbles, interlayered with mm-thick anastomosed greenish-purple levels made up of white mica (muscovite-paragonite s.s.), chlorite and epidote, the latter commonly displaying strong LREE and Th enrichments.
The metamorphic minerals are syn- to post-kinematic with respect to a metamorphic foliation, which is folded and locally crosscut by coarse-grained granoblastic calcite domains.
The Valdieri Marbles are cut by at least two orders of tectonic foliations and deformed by folds, faults and fractures belonging to regional systems well known in the surrounding region.
The marbles are locally crossed by mm- to dm-thick veins filled with calcite, quartz and Fe-rich dolomite. The vein minerals are characterized by the occurrence of abundant H_2O-CO_2 inclusions showing (at room T) $LH_2O \pm LCO_2 + VCO_2$ assemblage, often coexisting with CO_2 vapour-rich inclusions, possibly as a result of heterogeneous entrapment.
The reported data document that the Valdieri Marbles are the result of a prolonged, polyphase history of strongly focused, fluid-assisted deformation and recrystallization that preceded the main regional Upper Oligocene-Miocene deformation phases. Such (re-)crystallization was not related to regional metamorphism, but to a localized flux of CO_2-rich hydrothermal fluids diffusing through the sedimentary succession via bedding surfaces and fractures and mainly affecting more permeable layers.

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Analogue modelling of syn-sedimentary folding in mountain forelands : example of the Pyrenean orogen.

Méline Salze, Jacques Malavieille*

Géosciences Montpellier, Université Montpellier 2, Place E. Bataillon, 34095 Montpellier cedex 5, France.
** now at Chrono-environnement, Université de Franche-Comté, 16 Route de Gray, 25000 Besançon, France.*

In the Jaca basin located in the south of the Pyrenées, we can observe creation of folds attributed to a Cretaceous-Tertiary foreland tectonic (Labaume et al., 2015). This plurikilometric syn-sedimentary foldings were formed during Pyrenean convergence, which started 83 million years ago. Lack of metamorphism suggests that they have been producted in shallow structural levels. Deformation mechanisms, evolution of folds and thrusts, involving large convergence, are studied at wedge scale through an experimental approach (Perrin et al., 2013). 2D analogue modelling are realised with a brittle-plastic deformed multilayer in a context of asymmetric kinematic, which represents subduction. Development and tilt of large folds and thrusts show a periodicity, which is generated by alternance of brittle-plastic layers. In foreland, recumbent folds involve a shear-induced asymmetric deformation regime via progressive unrolling of synclinal hinges. Based on new experiments of sizing, the experimental configuration has been improved. The plasticine's rheological properties are characterized in order to model plastic layers. These are elasto-plastic materials which harden while distorting. This plasticine constitutes a good analogue of folded rocks of the upper crust, in orogenic wedge. It shear-resistance is decreased by a mix of 95% plasticine and 5% vaseline oil. The objective is to be better sized compared to the natural prototype. In experimental models, sizing allows to simulate mechanisms of syn-sedimentary folds formation. A structural study in Jaca basin highlights a plastic deformation in syn-sedimentary fold. Thus, a relation is established between the natural case and the experimental model. The model includes surface processes (sedimentation) and a structural inheritance. It is based on a cross-section of the area studied. The final state of the model is compared to the current field cross-section. This study gives a better understanding of the rheology's role and the mechanisms controlling the foldings, during the orogenic wegde growth.

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Thermochronology of the easternmost Central Alps: what drives exhumation during collision?

Sauton, C.[1], Rosenberg, C.[1], Barbarand, J.[2], Gautheron, C.[2], Pik, R.[3], Loget, N.[1], R., Rabaute, A.[1], Bellahsen, N.[1]

1: ISTeP, UPMC, Paris, France, 4 place Jussieu, 75252 Paris cedex 05
2: GEOPS - CNRS 8148, Université Paris sud; 91405 Orsay Cedex
3: CRPG Université de Lorraine, Vandoeuvre-Lès-Nancy Cedex

The Austroalpine domain is a remnant of the Adriatic margin and represents the highest unit of the collisional alpine nappe-stack. This unit covers the European plate while being dissociated from the Adriatic lithospheric mantle. In the easternmost Central Alps the Austroalpine domain corresponds to the Ötztal/Campo basement units, east of the Engadine Window and west of the Brenner Fault. The continuous exposure of Austroalpine nappes in this area, from the front of the chain, to the Insubric Line, points to the small amount of exhumation that has taken place throughout collision. Everywhere else in the Central Alps, the Austroalpine nappes are largely eroded. Based on combined surface data and P-wave seismic tomography, it is suggested that a lower crustal wedge of Adriatic origin underthrusted ~ 60 km of Alpine crust, north of the Insubric Line (Rosenberg and Kissling, 2013). Collisional shortening is small, estimated to 15-30 km at the northern front of the chain (Ortner et al., 2014) and additional structures localizing collisional shortening are not known further south, except for the Insubric Line itself.
From a geomorphological point of view, this area shows a mean topography comparable to that of the westernmost

Central Alps with, however, a smaller mean relief. In addition, the eastern Central Alps are characterized by a plateau-type topography that is not observed in the western Central Alps.
We carried out thermochronological investigations to constrain both the rates and the time of exhumation along a N-S, 80 km long profile, in this area. We performed zircon and apatite (U-Th)/He and apatite fission track dating on 10 Austroalpine samples. The thermal history of each sample since 100 Ma has been computed using the HeFTy software (Ketcham, 2005). Comparison of temperature-time models of the different samples show that one event of increased cooling rate took place during collision, and started at ~ 30 Ma in the southernmost sample of our section, and between 15 and 10 Ma for the other samples of the section. Given the lack of known large-scale thrusts and folds of collisional age in the area of our samples, we interpret the faster cooling stage starting at 15 Ma (~ 6-8 °C/Ma) as the result of the inferred lower crustal indentation of the Adriatic wedge. The age of faster cooling, hence of exhumation, described above, is consistent with the inferred ages of thrusting in the Southern Alps, which must be responsible for the detachment and formation of the lower crustal wedge. The attribution of exhumation to the latter Adriatic wedge, is also consistent with the plateau-type topography of the area, which was uplifted by a similar amount everywhere on top of the lower Adriatic crustal wedge.

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Fundamental strain localization mechanisms during continental collision with application to the Alpine orogeny

*Schmalholz, Stefan; Jaquet, Yoann; Duretz, Thibault; Bauville, Arthur**

Institute of Earth Sciences, University of Lausanne, CH-1015 Lausanne, Stefan.schmalholz@unil.ch
**now at: Institute for Geosciences, University of Mainz, Germany*

Strain localization during continental collision is responsible for the formation of orogenic wedges, tectonic nappes and ductile shear zones. However, the mechanisms controlling strain localization are still debated. This contribution focuses on mechanisms which can generate ductile shear zones with continuous deformation, that is, discontinuous deformation due to for example fracturing or frictional sliding is not considered. Three strain localization mechanisms are discussed which may be considered as fundamental mechanisms because (1) they operate for basic rheologies (such as linear or power-law viscous flow laws, or linear viscoelastic flow law), (2) the material properties remain constant during deformation (no material softening) and (3) they can occur in single-phase material (i.e. no porous material, no softening due to fluid-rock interaction or mineral reactions etc.). The three mechanisms are (1) kinematic strain localization, (2) structural softening (geometric instability), and (3) thermal softening. For kinematic strain localization the geometrical configuration or the kinematics outside the ductile material can impose a localization of strain, for example, the flow around mechanically strong objects or a brittle fault (velocity discontinuity) above or below the ductile material. Kinematic strain localization is independent of the material properties and flow laws. Kinematic strain localization is here applied to the formation of the Helvetic nappes which have been sheared-off from half grabens during the Alpine orogeny. Geometric instabilities such as necking or folding cause structural softening and strain localization in deforming layered rocks. In viscous multi-layers undergoing extension, localized shear zones can develop (additionally to necking) when both stiff layers and weak matrix are power-law viscous. During shear zone formation, the strength of the multi-layer decreases although the material parameters (stress exponent and reference viscosity) remain constant (no material softening). Such strength decrease is termed structural softening. Strain localization due to structural softening is applied to outcrop scale shear zones observed in deformed sedimentary rock in the Helvetic nappe system. Thermal softening is based on the conversion of mechanical work into heat and the decrease of ductile rock strength (effective viscosity) with increasing temperature. Thermal softening can generate shear zones with an intrinsic thickness of several kilometres for typical lithospheric deformation conditions. Thermal softening can be intensified in viscoelastic material when stored elastic strain energy is released during shear zone formation. Thermal-softening is applied here to explain the self-consistent formation of the Alpine orogenic wedge during continental collision and the propagation of thrust-type ductile shear zones towards the foreland. Two-dimensional numerical simulations of the three strain localization mechanisms will be presented and the applications to structures and observations in the Alps will be discussed.

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On the formation of the arc of the Western Alps and the Alps-Apennines transition

Schmid, S.M. & Kissling E.

Institute of Geophysics ETH, 8092 Zürich, Switzerland (stefan.schmid@erdw.ethz.ch)

The formation of the arc of the Western Alps is associated with WNW-directed indentation of the rigid Ivrea mantle geophysical body formed by mantle rocks that are part of the Adria lithosphere, partially exhumed already during mid-Jurassic rifting. The geometry of the Ivrea body is well constrained by a high-resolution 3-D P-wave model of the Alpine crust (Diehl et al. 2009) that our contribution integrates into a series of Alpine transects across the Western Alps. Oligocene (35-25 Ma) top-WNW indentation of Ivrea mantle was preceded by dextral transpression in the future Western Alpine arc during Eocene collision, confined between dextral shearing along the Tonale-Simplon-Valais strike slip zone in the N and a sinistral strike slip zone near Cuneo in the S. A third stage of arc formation is related to the opening of the Ligurian-Provencal and Tyrrhenian basins starting at around 30 Ma, affecting the Alps-Apennine transition zone from Mid-Miocene times onward. It led to oroclinal bending severely affecting the Ligurian Alps and associated with N-directed thrusting of the Ligurian Alps including the Tertiary Piedmont basin along the Apennines front in the Monferrato and Torino Hills; the southern part of the Western Alps arc was affected by ongoing Apennines orogeny.

Alps and Apennines are two orogens characterized by opposite subduction polarity. However, we argue that the Alps, characterized by a lower plate position of the European margin, formerly continued all the way to Corsica and the Northern Apennines Internal Ligurides further to Calabria, Peloritani Mts., Kabilies into the Betics until some 30 Ma ago, following ideas proposed by Elter & Pertusati (1973) and Michard et al. (2002). The West Ligurian Ocean, i.e. the SE-ward continuation of the Piemont-Liguria Ocean of the Alps proper, was closed between Europe-Iberia and the ALKAPECA micro-continent, while the East Ligurian Ocean remained open (Handy et al. 2010). Mantle lithosphere delamination and negative buoyancy of the still open East Ligurian Relic Ocean induced a change in subduction polarity, associated with severe roll back of the Adria continental lithosphere and adjacent East Ligurian Ocean. It is this roll-back that led to the Apennines orogeny, i.e. thrusting of the East Ligurian Ocean (preserved in the external Ligurides) together with parts of the former Alps (Internal Ligurides, Calabria and Peloritani continental slices) onto the Adria continental margin. Rollback and Apennines thrusting was associated with massive extension in the upper plate leading to the opening of the Ligurian-Provencal and Tyrrhenian basins and the rotation of Corsica-Sardinia. The above described oroclinal bending affecting the Ligurian Alps occurred during the final stages of Apennines orogeny in Mid-Miocene to recent times when the Ligurian Alps eventually became part of the Apennine orogen.

This demands that, in the Eocene, there must have been a major along-strike change within the Alps and their southwestward continuation. Continent-continent collision in the Alps of Eastern Switzerland and Austria led to the suturing of the European plate (including the Briançonnais micro-continent) with the Adria plate (Austroalpine nappes) along the Piemont-Liguria oceanic suture. In the Western Alps, however, there is no Austroalpine upper plate; the Sesia Zone with its high-p history is clearly in a lower plate position below the Adria margin including the Ivrea Zone. Instead, the upper plate in the Western Alps was formed by the East Ligurian Ocean lacking high-pressure overprint and only preserved in a few places such as, for example the Montgenèvre ophiolites. Further SE it is the East Ligurian relic ocean that formed the upper plate.

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Analysis of Cretaceous to Miocene ductile and brittle fault systems in Austroalpine units to the southeast of the Tauern Window (Eastern Alps)

Schuster Ralf & Ilickovic Tanja

Neulinggasse 38, 1030 Vienna Austria, Geologische Bundesanstalt ralf.schuster@geologie.ac.at, tanja.ilickovic@geologie.ac.at

The eastern part of the Tauern Window and the Austroalpine units immediately to the south of it (in the Kreuzeck and Sadnig Mountains) were in the focus of structural and geochronological studies in the past years (e.g. Schmid et al. 2013; Wölfler et al. 2014). While for the Subpenninic and Penninic units within the frame of the window detailed maps are available, the Austroalpine part and the fault pattern therein were shown only schematically and inconsistent in published overview maps. In this contribution we present additional structural and geochronological data from the area and a detailed tectonic map prepared by mapping in scale 1:10.000 and by the use of a high resolution digital elevation model. The map shows the interference and overprint relationship of the Oligocene and Miocene fault systems an gives the opportunity to attribute the pre-existing Ar-Ar, Rb-Sr and fission track ages to individual tectonic units and to reconstruct the structural evolution of the area in much more detail then before. From bottom to the top the tectonic column of the study area includes the following elements: The Sonnblick nappe of the Subpenninic unit consisting of huge masses of deformed Varicsan granites and some paragneisses is overlain by several Penninic and Subpenninic nappes and slices composed mainly out of Permian to Cretaceous metasediments. These units are characterised by a dominant Alpine (Oligocene-Miocene) structural and metamorphic imprint. Above Lower Austroalpine units including Permian to Triassic metasediments ("Alpiner Verrucano") and phyllonites (Sadnig Complex) with a penetrative Alpine (Eoalpine?) imprint followed by a Variscan metamorphic basement (Melenkopf Complex) are present. Upper Austroalpine units are represented by the Prijakt nappe characterised by an Eoalpine (Cretaceous) overprint and the tectonically uppermost Kreuzeck-Gailtaler Alpen nappe showing well preserved pre-Alpine (Variscan and Permian) assemblages and textures. This tectonic column is dissected by an Eocene-Oligocene and a Miocene fault pattern. Eocene-Oligocene NW-SE trending dextral faults include a precursor of the Mölltal fault system and the Ragga-Teuchl fault system. The latter is steeply dipping and E-W trending and represented by a several deca-meter wide cataclastic fault zone which shows a dextral offset. In the western part of the Kreuzeck Mountains the fault forms the boundary between the Kreuzeck-Gailtaler Alpen nappe and the Prijakt nappe, whereas in the east it cuts through the Prijakt nappe which contains eclogites only to the north of the Ragga-Teuchl fault. The Ragga-Teuchl fault is cut off by the Miocene Mölltal fault system in the East and by the Zwischenbergen fault system in the West. The Miocene Mölltal fault system forms the boundary of the Prijakt nappe in the Kreuzeck Mountains towards the Penninic and Subpenninic units in the Reiseck Mountains towards the Northeast. In the North it does not cut into the Tauern Window but it seems to continue into the E-W orientated frame of the Tauern Window. There the schistosity in the Penninic and Lower Austroalpine units is dipping to the South and shows a stretching lineation dipping towards SSE with a sinistral motion. The Zwischenbergen fault system separates parts of the Kreuzeck from the Sadnig Mountains. It is WSW-ENE orientated, sinistral and splits near to its ENE end into a number of SW-NE orientated parallel faults. Furthermore a branch of the Zwischenbergen fault system reactivates the western part of the Ragga-Teuchl fault with a sinistral offset. The SW-NE orientated faults are cut off at the boundary of the Tauern Window, but in its vicinity they show an increasing south directed dip slip component. In combination with the thermochronological data the downward migration of brittle deformation during cooling of the different tectonic levels can be demonstrated. Even if space problems lead to complex overprinting relations especially at the triple junctions of the faults the movement of the brittle blocks can be reconstructed properly.

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Curie temperature depths in the Alps and the Po Plain (northern Italy): evidence for a hot crust along maximum crustal thickness zones of the Alps

Speranza, Fabio[1], Minelli, Liliana[1], Pignatelli, Alessandro[1], and Gilardi, Matteo[2]

1- Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy, Emails: fabio.speranza@ingv.it; liliana.minelli@ingv.it, alessandro.pignatelli@ingv.it
2- ENI S.p.A., Exploration & Production Division, Via Emilia 1, 20097 San Donato Milanese, Italy. Email: matteo.gilardi@eni.com

Although hot Alpine chains are theoretically put forward by several geodynamic models, real heat flow data from the orogens are contradictory, and do not seem to systematically document hot belts. Data from the Italian Alps yielded in the past heat flow values ranging between 45 and 80 mW/m2 (Cataldi et al., 1995), suggestive of a cold to intermediate crust, but a recent data compilation and re-evaluation by Pasquale et al. (2012) raised heat flow values from the internal part of the Alps to 80-90 mW/m2. However, heat flow data of the Italian Alps were gathered either in shallow wells (depth < 1 km) or by road/railways tunnels, thus likely biased by shallow hydrological circulation of cold meteoric waters.
Here we report on the spectral analysis of the aeromagnetic residuals of the Alps and the Po Plain (northern Italy) to derive the Curie point depth (CPD), assumed to represent the 550°C isotherm depth. We analysed both the aeromagnetic residuals of northern Italy gathered by Agip (now Eni) and the recent EMAG2 compilation. We used the centroid method on 44 and 96 (respectively) 100x100 km2 windows considering both a random and a fractal magnetization distribution, but found that, at least for the Alps, the fractal model yields unrealistically shallow CPDs. Analyses considering a random magnetization model give CPDs varying between 12 and 39 km (22 to 24 km on average considering the two data sets, Figure 1) in the Po Plain, representing the Adriatic-African foreland area of the Alps, in substantial agreement with recently reported heat flow values of 60-70 mW/m2. In the Alps, the Eni data set yields shallow CPDs ranging between 6 and 23 km (13 km on average). EMAG2 analysis basically confirms the "hot" Alpine crust, but reduces it to three 50 to 100 km wide patches elongated along the chain, where CPDs vary between 10 and 15 km. Such "hot" Alpine domains occur in correspondence of maximum (>40-45 km) crustal thickness zones of the Alps, whereas no relation is apparent with local geology. Assuming an average crustal thermal conductivity of 2.5 W/m°C and a steady-state conductive model, CPDs from the hot zones of the Alps translate into heat flow values of 100-110 mW/m2, that are slightly higher than the 80-90 mW/m2 values recently reported for the internal part of the chain. Thus we quantify to ~20% the cooling effect of cold-water

circulation on the total heat flow of the high-relief Alpine zones, consistently with previously published estimates.

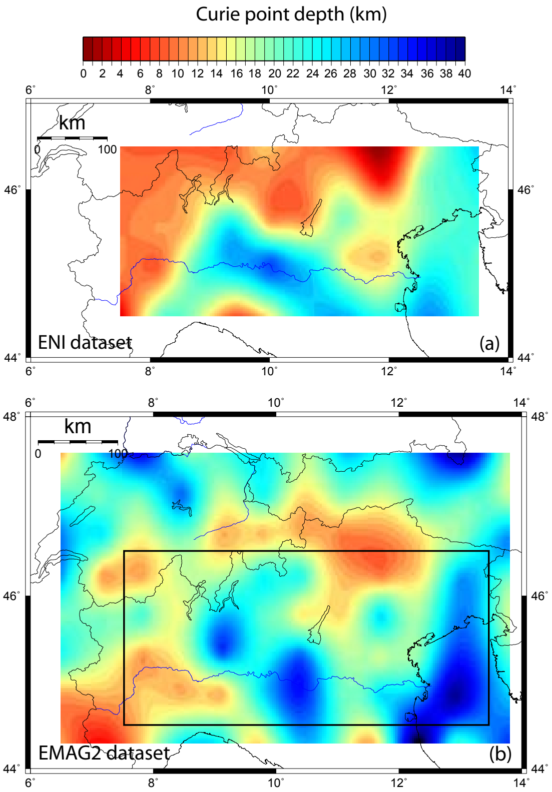

Figure 1. Curie point depths (below sea level) obtained by spectral analysis of the Eni (a) and EMAG2 (b) aeromagnetic residuals. Maps were obtained considering a random magnetization distribution in the crust. Black box in b represents the area resolved with the Eni dataset a.

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Neotectonic rotations in the Orava–Nowy Targ intramontane basin (Western Carpathians): an integrated palaeomagnetic and fractured clasts study

Antek K., Tokarski[a], Emő Márton[b], Ania Świerczewska[c], Jurek Zasadni[c], Józek Kukulak[d], Adam Fheed[c]*

a Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Cracow, Kraków, Poland, ndtokars@cyf-kr.edu.pl
b Geological and Geophysical Institute of Hungary, Palaeomagnetic Laboratory, Budapest, Hungary, paleo@mfgi.hu
c AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Kraków, Poland, swiercze@agh.edu.pl
d Institute of Geography, Pedagogical University of Cracow, Kraków, Poland, jkukulak@ap.krakow.pl

The objectives of this contribution are: (1) promotion of application of fractured clasts analysis in conglomerates for regional stress reconstructions and (2) to advance reconstruction of the Western Carpathians structural development. Our results show that the Neogene fill of the Orava-Nowy Targ Intramontane Basin underwent CCW rotation of over 20o. We infer that the rotation terminated after 8 Ma and was related to dextral shift along NW-SE to NNW-SSE trending faults at the NE termination of the Mür-Žilina Fault Zone. Our results show that, fractured clasts can be good tool for regional tectonic reconstructions. The tool is especially useful when other tectonic tools are scarce or absent. Results of our palaeomagnetic study and fractured clasts analysis verify and supplement each others. In the studied case, palaeomagnetic results allow to distinguish between regional stress field rotation and rotation of the Orava-Nowy Targ Basin Neogene fill, whereas, results of fractured clast analysis help to constrain the age of rotation.

Acknowledgements: This research was funded by the award of grant from the Polish State budget funds for scientific research (research project N N307 057434) to Ania Świerczewska and by Hungarian Scientific Research Fund (OTKA, project no K105245)

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U-Pb zircon geochronology of the Ligurian ophiolites (Northern Apennine, Italy): implications for continental break-up to slow seafloor spreading

Tribuzio Riccardo[1], Garzetti Fabio[1], Corfu Fernando[2], Tiepolo Massimo[3], Renna Maria Rosaria[4]

1 Dipartimento di Scienze della Terra e dell'Ambiente, Università di Pavia, Italy, tribuzio@crystal.unipv.it
2 Department of Geosciences, University of Oslo, Norway, fernando.corfu@geo.uio.no
3 Dipartimento di Scienze della Terra "Ardito Desio", Università di Milano, Italy, massimo.tiepolo@unimi.it
4 Dipartimento di Fisica e di Scienze della Terra, Università degli Studi di Messina, Italy, mrenna@unime.it

The fragments of Jurassic oceanic crust exposed in eastern Liguria (Northern Apennine, Italy) are either associated with continental lithosphere material (External Ligurian ophiolites), or bear structural and compositional resemblances to slow spreading ridge crust (Internal Ligurian ophiolites). To acquire new information about the transition from continental break-up to slow seafloor spreading, we carried out a U-Pb geochronological study of zircons from the eastern Ligurian gabbroic bodies. Zircons were separated from seven samples and analyzed for U-Pb isotopes by laser ablation ICPMS and isotope dilution TIMS. The zircons were also investigated for morphology, internal structures, inclusions and chemistry. These characteristics reveal remarkable similarities to zircons collected from modern oceanic crust. Taken as a whole, the U-Pb zircon dates obtained for the eastern Ligurian ophiolites range from ~165 to ~161 Ma, thereby arguing against previous geochronological investigations indicating a period of ~26 Ma for the formation of the

Ligurian gabbroic crust. The time interval intervened from onset of gabbroic crust intrusion in the marginal domain of the Ligurian Jurassic basin to configuration of a "slow spreading ridge type" crust was most likely <5 Ma. New insights into the opening mechanisms of the Jurassic basin are provided.

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The deep structure of the Alps: What can we learn from the Pyrenean orogen?

Tugend Julie[1], Manatschal Gianreto[1], Mohn Geoffroy[2] and Chevrot Sébastien[3]

1- Institut de Physique du Globe de Strasbourg; UMR 7516, Université de Strasbourg/EOST, CNRS, 1 rue Blessig, F-67084 Strasbourg Cedex, France. tugend@unistra.fr; manat@unistra.fr
2- Géoscience Environnement Cergy, Université Cergy-Pontoise, F-95 000 Cergy, France. Geoffroy.Mohn@u-cergy.fr
3- Observatoire Midi Pyrénées; UMR 5277, Université Paul Sabatier/IRAP, CNRS, Toulouse, France. schevrot@irap.omp.eu

Both the Pyrenean and Alpine belts represent collisional orogens resulting from the inversion of former hyperextended rifted margins. Refraction and reflection seismic data from present-day rifted margins show that such hyperextended domains (extremely thinned continental crust and/or exhumed serpentinized mantle) are very common and form wide areas between unequivocal continental and oceanic domains. Integrating these new observations and exploring their role during reactivation may result in alternative interpretations of the lithospheric structure of Alpine-type orogens.
The Pyrenees result from the inversion of a Late Jurassic to Cretaceous hyperextended rift system eventually floored by oceanic crust in the Bay of Biscay. New tomographic images across the orogen unravel the occurrence of a north-dipping velocity anomaly (Chevrot et al., 2014) that we interpret as former hyperextended domain subducted/underthrust during the early stages of convergence. This interpretation contrasts with the classical assumption that the subducted material is made of lower crustal rocks only. Our alternative interpretation may explain both the attenuation of the velocity anomaly at depth observed on tomographic images and the emplacement of remnants of hyperextended domains in the internal parts of the orogen. This interpretation also suggests that collisional processes were mainly controlled by the relatively well-imaged former European margin that acted as an indenter, illustrating the major role, even though complex, of rift inheritance in structuring the Pyrenean orogen.
The rift-related pre-collisional architecture of the Pyrenees show many similarities with that proposed for the Alps; although the width of the hyperextended and in particular of the proto-oceanic domains is little constrained for the Alpine domain. However, in contrast with the Pyrenees, remnants of these domains are largely affected by orogen-related deformation and show a high pressure metamorphic overprint in the Alps (Mohn et al., 2014; Beltrando et al., 2014). Nevertheless, in spite of the occurrence of these high pressure rocks constituting the internal parts of the Alps, the overall crustal and lithospheric structure looks surprisingly comparable. This similarity raises the question of the nature of the roots (hyper-extended material or lower crustal rocks?) and of the control of rift-inheritance on the final stages of convergence for Alpine-type orogens.

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Miocene to recent kinematics and exhumation of the Mur-Mürz strike-slip fault (Eastern Alps) illustrating direct interplay with surrounding lithospheric scale processes.

van Gelder, I.E.[1,2], Willingshofer, E.[1], Andriessen, P.A.M.[2]*

1 - Utrecht University, Faculty of Geosciences, PO Box 80021, 3508 TA, Utrecht, The Netherlands (i.e.vangelder@uu.nl)
2 - VU University, Faculty of Earth and Life Sciences, Amsterdam, The Netherlands;

Understanding the Miocene to recent tectonic evolution of the Eastern Alps-Pannonian Basin transition is of critical importance to comprehend the relationship with the underlying lithospheric processes. The transition is influenced by multiple tectonic processes during the Miocene to recent time interval, namely: subduction of Adria and related northward convergence, lateral extrusion of the Eastern Alps, back-arc basin formation, inversion and regional uplift. The interaction of these processes are however not well constrained along the Mur-Mürz strike-slip fault that is located at the eastern end of the Eastern Alps and terminates in the west of the Pannonian basin, the Vienna basin to be precise. Hence, insights in the kinematics of the Mur-Mürz Fault (MMF) and associated vertical motions across the fault will provide new constraints on the Miocene to recent tectonic evolution of the Eastern Alps-Pannonian basin transition.
The MMF is a sinistral en-echlon strike-slip fault bounding the Styrian crustal block, including the Styrian basin, and facilitates extrusion to the east in response to the opening of the Pannonian back-arc basin and coeval northward motion of Adria. By means of detailed kinematic analysis and new supplementary (low temperature) thermochronological data the tectonic

evolution and interplay of the above stated processes has been analysed along the MMF.
The kinematic analysis indicates a similar tectonic evolution for the MMF compared to the Vienna Basin and other strike-slip faults in the Eastern Alps. Four separate deformation phases could be distinguished, were the first three reflect lateral extrusion related tectonics but the last phase reflects tectonics controlled by the Pannonian Basin inversion. The thermochronological results indicate very scattered apatite fission track cooling ages, which vary between 50-4 Ma, but with an overall youngening trend towards the east. Complementary zircon fission track ages are between 90-53 Ma and also reveal a similar youngening trend to the east. Both the apatites and zircon cooling ages cannot be directly linked to lateral extrusion processes, as expected due to little vertical motion associated with extrusion. We rather suggest that the cooling ages are related to regionl denunadation with a tilt of the area as reflected by the youngening trend. To conclude, the results suggests that the tectonic evolution of the MMF is intrinsically related to processes that occur both in the Eastern Alps and the Pannonian Basin during the Miocene to recent time interval but that the regional cooling and uplift reveals a more complex tectonic evolution probably not directly linked to Miocene extrusion but deep-seated lithospheric processes.

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Lateral extrusion of the upper plate in response to subduction of a non-rigid continental plate; analogue modelling and application to the Eastern Alps.

van Gelder, I.E., Willingshofer, E., Sokoutis, D.

Utrecht University, PO Box 80021, 3508 TA, Utrecht, The Netherlands; Corresponding author: i.e.vangelder@uu.nl

Novel lithospheric scale analogue models reveal the tectonic interplay between lateral extrusion and subduction processes. Traditionally, lateral extrusion tectonics are modelled by incorporating a rigid indenter triggering extrusion of a crustal wedge towards an unconstrained boundary at a high angle to the indentation direction [e.g., Ratschbacher et al., 1991; Rosenberg et al., 2004]. These models have been used to explain extrusion tectonics, as observed in the Eastern Alps, driven by northward 'indentation' of the Adriatic plate provoking extrusion towards the east where the east-directed opening of the Pannonian Basin acted as an unconstrained (weak) boundary. However, recent tomographic studies suggest that lateral extrusion is coeval with subduction of the Adriatic plate rather than lithosphere-scale indentation [e.g., Lippitsch et al., 2003].
We present a series of analogue models that refine the traditional extrusion model by including subduction of a non-rigid plate. To quantify the tectonic response of extrusion on subduction the models are compared to a reference model that is constructed according to the traditional setting. Besides testing compatibility between lateral extrusion and subduction processes, the model series also focused on gaining insights in the first order boundary conditions and mechanisms, such as: (a) variations in the mode of strain partitioning at the surface and in-depth in response to rheological variations, (b) the effect of different slab geometries, and (c) the timing of events, e.g. subduction prior to the activation of an extensional (unconstrained) boundary.
The experimental results emphasize that extrusion and subduction are compatible processes that can operate simultaneously. Furthermore, the models suggest that the extruding East Alpine lithosphere is weak but coupled, implying that lateral extrusion is a lithospheric-scale rather than a crustal-scale process.

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Exhumation of HP-LT units of the internal Briançonnais zone, new constraints from U-Th-Pb dating on allanite minerals and geodynamic implications.

Verly Aude[1], Dumont Thierry[1], Lanari Pierre[2]

1- Institut des Sciences de la Terre, CNRS, University of Grenoble Alpes, 1381 rue de la Piscine, 38041 Grenoble cedex 9, France. aude.verly@e.ujf-grenoble.fr ; thierry.dumont@ujf-grenoble.fr
2- Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3 CH-3012 Bern, Swiss pierre.lanari@geo.unibe.ch

During the Alpine collision, the internal Briançonnais units have been extruded together with the Liguro-Piedmontais paleo-wedge. This early collisional stage strongly influenced the present day structure of the tectono-metamorphic units and marks the transition between continental subduction and collision. Consequently, it seems critical to document this early collisional stage and to constrain the Pressure-Temperature-time conditions at which it occurred. In order to study this subduction- collision transition, the Acceglio-Longet anticline (western Queyas) was selected and investigated. This continental unit, derived from a marginal rift shoulder, is made of crystalline basement with an extremely reduced Mesozoic sedimentary cover. The aim of this work is to investigate the tectono-metamorphic relationships between this unit and the oceanic Schistes Lustrés units which are thrust over it.
Metapelite from both continental and oceanic units exhibit similar mineral parageneses, with relics from the HP-LT stage (occurring at 450±25°C and 13.5±1.5 kbar in the Acceglio zone, see Schwartz & al., 2000) such as glaucophane and rutile partially replaced by greenschist phases such as chlorite and low-Si K-white mica. This latest assemblage is related to the eastward extrusion of the continental units. In details, the main foliation plane is underlined by chlorite + phengite + sphene ± amphibole and is overprinted by an oblique crenulation cleavage. This second fabric is underlined by the overgrowth of muscovite over phengite rims, new chlorite, albite porphyroblasts allanite and calcite. Quantitative X-ray

maps have been acquired using an electron microprobe in order to measure the chemical variability of the mineral phases and to constrain the local bulk composition of the retrogressed domains. Rock specific equilibrium phase diagrams – computed using Theriak-Domino – predicts that chlorite and K-white mica crystallized at 400±50°C and 7±2 kbar.

U-Th-Pb micro-dating on allanite has been performed using a LA-ICP-MS and a spot size between 32 and 42 µm. Allanite crystals from both Schistes lustrés and Acceglio units yields similar Th-ages of 33.92±1.88 Ma and 33.38±1.55Ma respectively. Allanite growth is related to the second metamorphic stage as allanite grains exhibits inclusions of muscovite and albite. These results suggest that both units were stacked before the time of allanite crystallization that occurred during the eastward extrusion.

This set of data shows that the internal Briançonnais zone and the surrounding oceanic metasediments have a common exhumation history from ~20 km depth up to the surface. The tectonic contact between the two units must have been emplaced in an early stage during the subduction. Later on, it has been only locally deformed and exhumed during the extrusion stage. At the orogen scale, the exhumation stage of this part of the internal zones seems to be synchronous with the Penninic thrust activation that occurred between 34-30 Ma (Simon-Labric et al., 2009) and with the exhumation of the internal crystalline massif of Dora Maira.

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Microseismic analysis of the Fribourg Lineament: An active fault zone in the Western Swiss Molasse Basin

Naomi Vouillamoz, Martinus Abednego*, Gilles Hillel Wust-Bloch**, Jon Mosar**

**6, Ch. du Musée, CH-1700 Fribourg, Earth Sciences Unit - University of Fribourg, naomi.vouillamoz@unifr.ch*

*** Tel Aviv University, Department of Geophysics and Planetary Sciences, P.O.B. 39040, Tel Aviv, 69978, Israel*

The Fribourg Lineament (FL) is a 30 km long N-S cluster of weak seismic activity (ML < 4.3). It is located in the Western Swiss Molasse Basin, east of Fribourg. Three series of events, which took place in 1987, 1995 and 1999 were located in the sedimentary cover at a depth of 2 km but identified as related to deep reaching structures carrying in size the potential for a magnitude 6 earthquake [Kastrup et al., 2007]. Nanoseismic Monitoring techniques [Joswig, 2008] were recently applied to characterize the seismic activity along the FL and analyze its relationship to local tectonic features. Two sparse seismic mini-arrays (UNIFR) were temporarily deployed above the FL to lower the present detection threshold of the Swiss seismological network (SED). The joint dataset (UNIFR & SED data) was then screened by sonogram analysis, whereby auto-adaptive noise filters are applied to enhance weak signal energy close to the noise threshold [Joswig, 2008; Sick et al., 2012].

Between 2009 and 2013, 305 events were detected within a 20 km radius area around Fribourg. Among these events, 34 only were also detected by the SED. All the seismicity is located at shallow depth (0.5-4 km) and therefore seems to be generated within the sedimentary cover. Based on a waveform similarity analysis, it was shown that 152 events cluster into four main earthquake families along the FL. A very high correlation factor was observed between earthquake sequences occurring over periods extending to a few months/years, suggesting that repeated ruptures occur on discrete fault segments along the FL. Given their low magnitudes (-2 < ML < 2.5), sources scale in the 10-100's meters range. Fault plane solutions computed for the stronger events indicate almost pure N-S left-lateral strike-slip rupture mechanisms [Deichmann et al., 2010].

The interpretation of seismic profiles identifies a N-S trending fault zone of up to 5 km wide within the Mesozoic layers, east of the city Fribourg. This disturbed zone appears to be decoupled from the basement and is thus interpreted as an inherited Mesozoic graben structure [Sommaruga et al., 2012]. This is corroborated by structural analyses of the Molasse Basin near Fribourg. A strongly deformed zone of N-S oriented left-lateral tear faults along-strike the FL [Ibele, 2011] suggests a reactivation of the underlying Mesozoic structures during Tertiary times. This may indicate that the FL concentrates repeated ruptures along a N-S pre-structured and damaged zone. The preferred N-S orientation of the damaged zone might account for an easier reactivation within the present day counterclockwise rotational stress field in the alpine foreland, which in turn may contribute to generate some of the local seismicity along the FL. Given the spatial extent of the seismicity clustering along the FL, it is not possible to rule out the occurrence of higher magnitude events (ML > 5-6).

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Coherence between geodetic and seismic deformation in a context of slow tectonic activity (SW Alps, France)

A. Walpersdorf[a], C. Sue[b], S. Baize[c], N. Cotte[a], P. Bascou[a], C. Beauval[a], P. Collard[d], G. Daniel[a,b], H. Dyer[a,e], J.-R. Grasso[a], O. Hautecoeur[f], A. Helmstetter[a], S. Hok[a,c], M. Langlais[a], G. Menard[m], Z. Mousavi[a,g], F. Ponton[a], M. Rizza[h], L. Rolland[i], D. Souami[j,k], L. Thirard[l], P. Vaudey[a], C. Voisin[a] and J. Martinod[a]

a ISTerre, Univ. Grenoble Alpes, CNRS, BP 53, 38041 Grenoble Cedex 9, France (andrea.walpersdorf@ujf-grenoble.fr
b Chrono-Environnement CNRS Univ Franche-Comté Besançon France
c IRSN/PRP-DGE/SCAN/BERSSIN, Fontenay-aux-Roses, France
d Géosciences Montpellier, Univ. Montpellier II, CNRS France,
e IMSRN, 680, Rue Aristide Berges, 38330 Montbonnot-Saint-Martin,
f EUMETSAT, Eumetsat Allee 1, 64295 Darmstadt, Germany,
g National Cartographic Center, Meraj Blv., Azadi Sq., Tehran, Iran,
h CEREGE, Univ. Aix-Marseille, CNRS, France,
i Géoazur, UNSA, CNRS, Sophia Antipolis, France,
j Univ. Pierre et Marie Curie, 4 place Jussieu, 75005 Paris, France,
k NAXYS, Univ. Namur, 5000 Namur, Belgium,
l INSA, 24 Boulevard de la Victoire, 67000 Strasbourg, France),
m EDYTEM, Université de Savoie, 73376 Le Bourget du Lac Cedex,

A dense, local network of 30 geodetic markers covering a 50 x 60 km² area in the southwestern European Alps (Briançon region) has been temporarily surveyed in 1996, 2006 and 2011 by GPS. The aim is to measure the current deformation in this seismically active area. The study zone is characterized by a majority of extensional and dextral focal mechanisms, along north-south to N160 oriented faults. The combined analysis of the three measurement campaigns over 15 years and up to 16 years of permanent GPS data from the French RENAG network now enables to assess horizontal velocities below 1 mm/yr within the local network. The long observation interval and the redundancy of the dense campaign network measurement help to constrain a significant local deformation pattern in the Briançon region, yielding an average E-W extension of 16 ± 11 nanostrain/yr. We compare the geodetic deformation field to the seismic deformation rate cumulated over 37 years, and obtain good coherencies both in amplitude and direction. Moreover, the horizontal deformation localized in the Briançon region represents a major part of the Adriatic-European relative plate motion. However, the average uplift of the network in an extensional setting needs the presence of buoyancy forces in addition to plate tectonics.

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Retro-wedge formation during collision: favourable mechanical conditions deduced from analogue and numerical modelling

Willingshofer, E.[1]; Sokoutis, D.[1]; Weekenstroo, M.[1]; Vogt, K.[1]; Gueydan, F.[2], Matenco, L.[1]

1 Faculty of Geosciences, Univ Utrecht, The Netherlands
2 Géosciences Montpellier, Univ. Montpellier II, CNRS France.

Continent-continent collision follows subduction of oceanic lithosphere and is expected to result in doubly verging orogenic wedges with well-developed retro-wedges on the overriding plate. We question this simple view and argue that retro-wedge formation is restricted to specific rheological conditions within the lower and upper plates as well as the plate contact; thus being the exception rather than the rule during collision.
We use a combination of physical analogue and numerical experiments to infer favourable rheological conditions for the development of retro-wedges. In both analogue and numerical experiments the contact between the colliding and neutrally buoyant continents is weak and represents the inheritance of a former subduction boundary. The degree of plate coupling however is not constant and is together with the rheological structures of the lower and upper plates, in particular the presence of decoupling horizons, key variable in this study.
Analogue and numerical models with strong decoupling at the plate boundary and at the Moho or the brittle-ductile transition of the incoming plate lead to outward propagating mountain belts by successive imbrication of upper crustal thrust sheets independent as to whether collision was preceded by subduction of oceanic lithosphere or not. Under these conditions, which are typical for subduction-dominated orogens like the Carpathians, the Dinarides or the Apennines, no significant retro-wedges with large-displacement retro-shears develop.
Transfer of strain to the upper plate is favoured when the degree of plate coupling is high, the crust of the colliding and in particular the subducting plate is strong and when the upper plate contains decoupling horizons (e.g. at the Moho or the brittle-ductile transition). Under such conditions large-scale retro-shears develop and deformation propagates outward on the upper plate to form a retro-wedge.
These analogue and numerical experiments provide insight in past rheological conditions of doubly verging mountain belts, demonstrating that retro-wedge formation is only possible under restricted rheological conditions.

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New high-resolution P-wave tomography model in the Alpine region

Liang Zhao[1], Marco G. Malusà[2], Anne Paul[3, 4], Xiaobing Xu[1], Stefano Solarino[5], Stéphane Guillot[3, 4], Stéphane Schwartz[3, 4], Thierry Dumont[3, 4], Qingchen Wang[1], Rixiang Zhu[1]

1 State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. Email: zhaoliang@mail.iggcas.ac.cn
2 Department of Earth and Environmental Sciences, University of Milano-Bicocca, Milan, Italy
3 Université Grenoble Alpes, ISTerre, Grenoble, France.
4 CNRS, ISTerre, Grenoble, France.
5 Istituto Nazionale di Geofisica e Vulcanologia, Genova, Italy.

The complex slab structure beneath the Alpine region is only partly resolved by previous geophysical data, leaving many geological issues widely open. Here, we present a new high-resolution tomography model constructed by inverting P-wave data with finite-frequency kernel formulations. The P-wave travel-time data are picked from 433 broadband seismic stations, both from permanent networks and temporary experiments (CIFALPS and PYROPE). Resolution tests for different depths and the featured velocity anomalies verify that the tomographic images capture the velocity heterogeneities in the upper mantle to depths of 600 km.

This model provides an improved image of the slab structure, and fundamental pin-points for the analysis of Cenozoic magmatism, (U)HP metamorphism and Alpine topography. We document the lateral continuity of the European slab from the Western to the Central Alps, and the down-dip slab continuity beneath the Central Alps, ruling out the hypothesis of slab breakoff. The steep European slab gets shallower at ~400 km beneath the Po Plain, where it lays below an evident low-velocity anomaly. Another low velocity anomaly extending down to the mantle transition zone is observed beneath the highest Alpine peaks, pointing to dynamic topography effects. A NE-dipping Adriatic slab, consistent with Dinaric subduction, is observed beneath the Eastern Alps, whereas the Adriatic slab is continuous along strike in the Northern Apennines, but shows major gaps at the boundary with the Southern Apennines, and becomes near vertical in the Alps-Apennines transition zone. Tear faults accommodating opposite-dipping subductions during Alpine convergence may represent reactivated lithospheric faults inherited from Tethyan extension.

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Alphabetic List of Contributions

Alphabetic List of Participants

Name	First name	email	Univ. / Lab / Organism / City
Abbas	Hassan	hassan.abbas@uniroma1.it	Sapienza Univ. of Roma
Agard	Philippe	philippe.agard@upmc.fr	UMPC paris
Bacenetti	Marco	marco.bacenetti@unito.it	Department of Earth Sciences, Univ. of Torino
Ballèvre	Michel	Michel.Ballevre@univ-rennes1.fr	Geosciences Rennes
Barale	Luca	luca.barale@unito.it	CNR IGG-GiRES, Torino
Bellahsen	Nicolas	nicolas.bellahsen@upmc.fr	Univ. Pierre et Marie Curie, Paris
Beltrando	Marco	marco.beltrando@unito.it	Univ. of Torino
Bergemann	Christian	christian.bergemann@unige.ch	Univ. of Geneva
Berger	Alfons	alfons.berger@geo.unibe.ch	Univ. of Bern
Bertok	Carlo	carlo.bertok@unito.it	Dipartimento Scienze della Terra - Univ. of Torino
Bertrand	Audrey	audreybertran@gmail.com	Hungarian Academy of Sciences, Budapest
Boutoux	Alexandre	alex.boutoux@laposte.net	UPMC, Paris
Burn	Marco	marco.burn@geo.unibe.ch	Univ. of Bern
Butler	Rob	rob.butler@abdn.ac.uk	Univ. of Aberdeen
Caer	Typhaine	typhaine.caer@gmail.com	Univ. of Cergy-Pontoise, Geosciences Environnement
Carminati	Eugenio	eugenio.carminati@uniroma1.it	Sapienza Univ. di Roma
Chevrot	Sebastien	sebastien.chevrot@get.obs-mip.fr	CNRS, Observatoire Midi Pyrenees, Univ. of Toulouse
Cirio	Raymond	cirio.raymond@wanadoo.fr	CBGA Briançon
Cvetkovic	Vladica	vladica.cvetkovic@rgf.bg.ac.rs	Univ. of Belgrade - Faculty of Mining and Geology
d'Atri	Anna	anna.datri@unito.it	Dipartimento di Scienze della Terra Univ. of Torino
de Broucker	Gilles	gdebroucker@gmail.com	Georegards, Les Curtillets
de la Taille	Camille	camille.de-la-taille@univ-savoie.fr	Univ. Savoie Mont Blanc, Chambery
Decarlis	Alessandro	decarlis@unistra.fr	CNRS, Univ. of Strasbourg
Dumont	Thierry	thierry.dumont@ujf-grenoble.fr	ISTerre, Grenoble
Duretz	Thibault	thibault.duretz@unil.ch	Univ. of Lausanne
Engi	Martin	engi@geo.unibe.ch	Univ. of Bern
Epin	Marie-Eva	meepin@unistra.fr	Univ. of Strasbourg
Faccenna	Claudio	faccenna@uniroma3.it	Univ. of Roma 3
Fodor	Laszlo	lasz.fodor@yahoo.com	MTA-ELTE Geological Res. Group Budapest
Giuntoli	Francesco	francesco.giuntoli@geo.unibe.ch	Univ. of Bern
Gnos	Edwin	edwin.gnos@ville-ge.ch	Natural History Museum of Geneva
Graham	Rodney	rod.graham01@gmail.com	Rod Graham Consulting, Wallingford
Grasso	Jean-Robert	jean-robert.grasso@ujf-grenoble.fr	ISTerre observatoire de Grenoble
Gruber	Marius	marius.gruber@unifr.ch	Univ. of Fribourg
Haupert	Isabelle	haupert@unistra.fr	Univ. of Strasbourg
Henry	Jean-Louis	henryjeanlouis@gmail.com	CBGA Briancon
Herman	Frederic	frederic.herman@unil.ch	Univ. of Lausanne
Hernandez-Moreno	Catalina	catalina.hernandezmoreno@ingv.it	INGV Roma
Horvath	Balazs	kyklad@gmail.com	Eotvos Lorand Univ.
Husson	laurent	laurent.husson@ujf-grenoble.fr	CNRS ISTerre Grenoble
Iglseder	Christoph	christoph.iglseder@geologie.ac.at	Geological Survey of Austria Vienna
Incerpi	Nicolo	nicolo.incerpi@unito.it	Univ. of Torino
Jaquet	Yoann	yoann.jaquet@unil.ch	Univ. of Lausanne
Jourdon	Anthony	jourdon@geoazur.unice.fr	Geoazur, CNRS, Univ. of Nice Sophia Antipolis
Kaestle	Emanuel	emanuel.kaestle@etu.upmc.fr	Univ. Pierre et Marie Curie Paris
Keil	Melanie	melanie.keil2@sbg.ac.at	Univ. of Salzburg
Kover	Szilvia	koversz@yahoo.com	MTA-ELTE Geological Research Group Budapest
Kufner	Sofia-Katerina	kufner@gfz-potsdam.de	German Research Centre for Geosciences Potsdam
Lagabrielle	Yves	yves.lagabrielle@univ-rennes1.fr	Geosciences Rennes
Lanari	Pierre	pierre.lanari@geo.unibe.ch	Univ. of Bern
Liao	Jie	jie.liao@erdw.ethz.ch	ETH Zurich
Luca	Martire	luca.martire@unito.it	Univ. of Torino
Luisier	Cindy	cindy.luisier@unil.ch	Univ. of Lausanne
Malusa	Marco	marco.malusa@unimib.it	Univ. of Milano-Bicocca
Manatschal	Gianreto	manat@eost.u-strasbg.fr	Univ. of Strasbourg

Manzotti	Paola	Paola.Manzotti@univ-rennes1.fr	Geosciences Rennes
Marthaler	Michel	michel.marthaler@unil.ch	Univ. of Lausanne
Martire	Luca	luca.martire@unito.it	Univ. of Torino
Marton	Emo	paleo@mfgi.hu	Geological and Geophysical Institute of Budapest
Masini	Emmanuel	emmanuel.masini@total.com	Total EP
Mateeva	Tsvetomila	mateeva@liverpool.ac.uk	Univ. of Liverpool
Matthews	Steeve	steve.matthews@frontierstructure.com	Frontier Structure Ldt
Miladinova	Irena	irenamil@uni-bonn.de	Steinmann-Institut fur Geologie, Univ. of Bonn
Minelli	Liliana	liliana.minelli@ingv.it	Istituto Nazionale di Geofisica e Vulcanologia, Roma
Mladenovic	Ana	ana.mladenovic@rgf.bg.ac.rs	Univ. of Belgrade - Faculty of Mining and Geology
Molinari	Irene	irene.molinari@erdw.ethz.ch	ETH Zurich
Mosar	Jon	jon.mosar@unifr.ch	Department of Geosciences - Univ. of Fribourg
Muntener	Othmar	othmar.muntener@unil.ch	Univ. of Lausanne
Munzarova	Helena	helena@ig.cas.cz	Inst. of Geophysics, CAS, Prague
Nestola	Yago	yago.nestola@unipr.it	Universite di Parma
Nievergelt	Peter	peter.nievergelt@erdw.ethz.ch	ETH Zurich
Palotai	Marton	marton.palotai@casp.cam.ac.uk	CASP, Cambridge
Palzer-Khomenko	Markus	markus.palzer@univie.ac.at	Univ. of Vienna
Paul	Anne	anne.paul@ujf-grenoble.fr	ISTerre, Univ. of Grenoble
Petri	Benoit	bpetri@unistra.fr	Univ. of Strasbourg
Pezzali	Irene	irene.pezzali01@ateneopv.it	Univ. of Pavia
Piana	Fabrizio	f.piana@csg.to.cnr.it	CNR IGG, Torino
Picard	Christian	christian.picard@univ-fcomte.fr	Univ. of Besancon
Pleuger	Jan	jan.pleuger@fu-berlin.de	Freie Universitaet Berlin
Plomerova	Jaroslava	jpl@ig.cas.cz	Inst. of Geophysics, CAS, Prague
Porkolab	Kristof	kristof.porkolab@gmail.com	Eotvos Univ., Dept. Applied and Physical Geology
Potin	Bertrand	bertrand.potin@ujf-grenoble.fr	ISTerre Grenoble
Rabin	Mickael	mickael.rabin@univ-fcomte.fr	Univ. of Besancon
Ragusa	Jérémy	jeremy.ragusa@unige.ch	Univ. of Geneva
Real	Christophe	christophe.real@univ-rennes1.fr	Geosciences Rennes
Replumaz	Anne	anne.replumaz@ujf-grenoble.fr	ISTerre Grenoble
Rosenberg	Claudio	claudio.rosenberg@upmc.fr	UPMC, Paris
Rolland	Yann	yrolland@unice.fr	Geoazur, Univ. of Nice Sophia Antipolis
Rossetti	Piergiorgio	piergiorgio.rossetti@unito.it	Univ. of Torino
Salze	Méline	meline.salze@gmail.com	Univ. of Besancon
Saric	Kristina	kristina.saric@rgf.bg.ac.rs	Univ. of Belgrade - Faculty of Mining and Geology
Schmalholz	Stefan	stefan.schmalholz@unil.ch	Univ. of Lausanne
Schmid	Stefan	stefan.schmid@erdw.ethz.ch	Institute of Geophysics ETH Zurich
Schuster	Ralf	ralf.schuster@geologie.ac.at	Geologische Bundesanstalt Vienna
Speranza	Fabio	fabio.speranza@ingv.it	INGV Roma
Sue	Christian	christian.sue@univ-fcomte.fr	Univ. of Besancon
Tribuzio	Riccardo	tribuzio@crystal.unipv.it	Univ. of Pavia
Tugend	Julie	tugend@unistra.fr	IPGS, Univ. of Strasbourg
van Gelder	Inge	i.e.vangelder@uu.nl	Utrecht Univ.
Verly	Aude	aude.verly@hotmail.fr	ISTerre Ggrenoble
Vouillamoz	Naomi	naomi.vouillamoz@unifr.ch	Univ. of Fribourg
Vrabec	Mirijam	mirijam.vrabec@ntf.uni-lj.si	Univ. of Ljubljana
Walpersdorf	Andrea	andrea.walpersdorf@ujf-grenoble.fr	ISTerre Grenoble
Willingshofer	Ernst	e.willingshofer@uu.nl	Faculty of Geosciences, Utrecht Univ.
Winterberg	Sascha	sascha.winterberg@erdw.ethz.ch	ETH Zurich
Zampieri	Dario	dario.zampieri@unipd.it	Univ. of Padova
Zhao	Liang	zhaoliang@mail.iggcas.ac.cn	Inst. Geol. & Geophys. Chinese Acad Sciences, Beijing